Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

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Light new physics at muon factories

Diego Redigolo

Talk based on

2006.04795 [hep-ph] with *L. Calibbi, R. Ziegler, J. Zupan*

2203.11222 [hep-ph] with *S. Knapen and Y. Jho*

work in progress with *S. Knapen, Y. Jho , K. Langhoff, T. Opferkuch*

Rare decays of SM particles as a probe of New Physics

Accidental symmetries play a crucial role in the Standard Model and testing their breaking with increasing precision is one of standard ways we expect New Physics to manifest itself at experiments

Rare decays of SM particles are standard candles to probe NP

muon rare decays are a great example

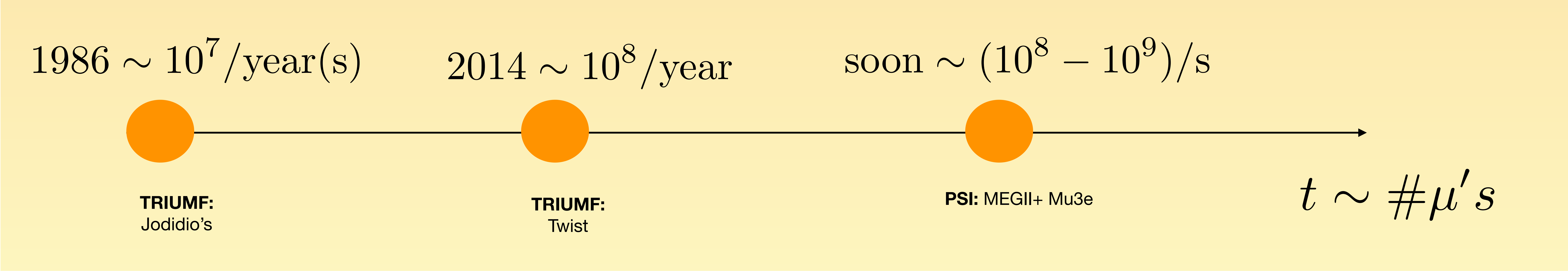
$1986 \sim 10^7/\text{year(s)}$ — **TRIUMF:** Jodidio's

$2014 \sim 10^8/\text{year}$ — **TRIUMF:** Twist

$\text{soon} \sim (10^8 - 10^9)/\text{s}$ — **PSI:** MEGII+ Mu3e

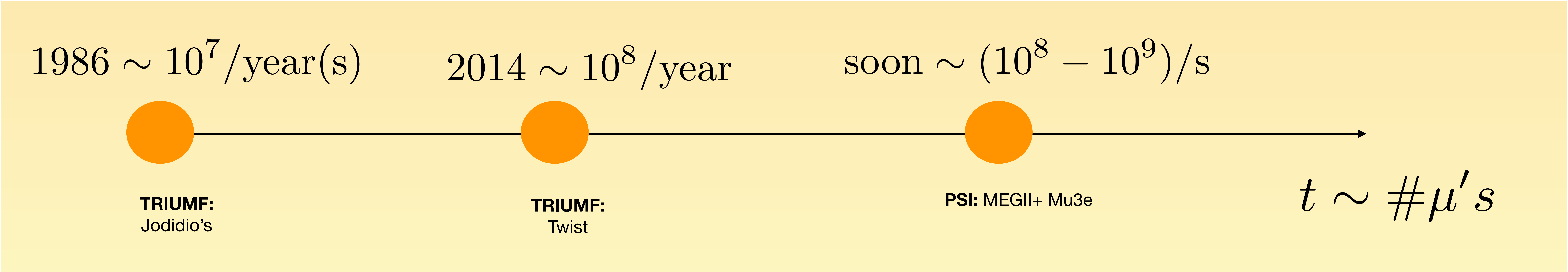
$t \sim \#\mu' s$

Goal of this talk



Goal of this talk

The goal of this talk is to show how rare decays of the muon which are usually thought as powerful probe of heavy new physics can also probe light new physics feebly coupled to the SM



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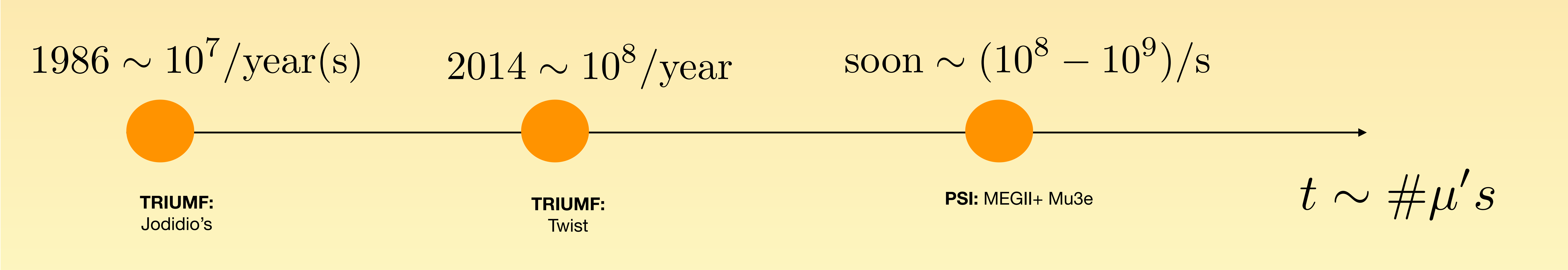

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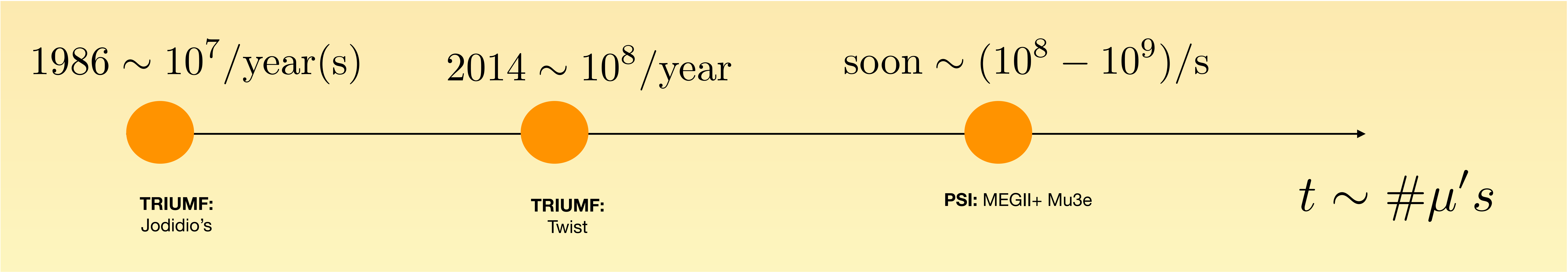

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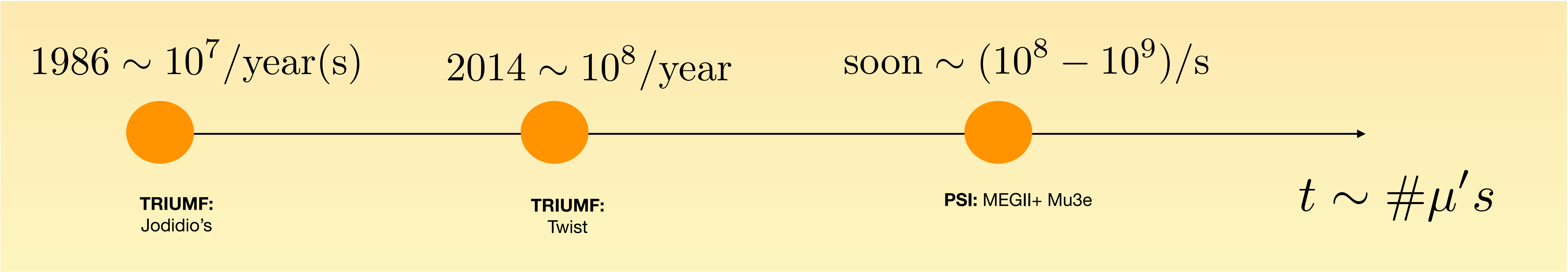
As a bonus we will show that this program can actually probe reasonable models



Heavy New Physics vs Lepton Flavor

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \dots$$

LFV @ dimension 6

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$U(1)_e \times U(1)_\mu$

Forbids $\mu \to e\gamma$

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$$\frac{C_{ij}^{(5)}}{\Lambda}(L_i H)(L_j H)$$

$$\mathrm{BR}(\mu \to e\gamma) \sim \frac{\alpha}{8\pi} \times \left(\frac{m_\nu}{M_W}\right)^4$$

obscenely small!

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$$\frac{C_{e\mu}^{(6)}}{\Lambda^2}\bar{L}\sigma^{\mu\nu} e H B_{\mu\nu} + \ldots$$

$$\mathrm{BR}(\mu \to e\gamma) \sim \frac{16\pi^2 v^6}{\Lambda^4 m_\mu^2} \times (C_{e\mu}^{(6)})^2$$

Sensitive to $\gtrsim 10^4$ TeV NP for $C_{e\mu}^{(6)} \sim 1$

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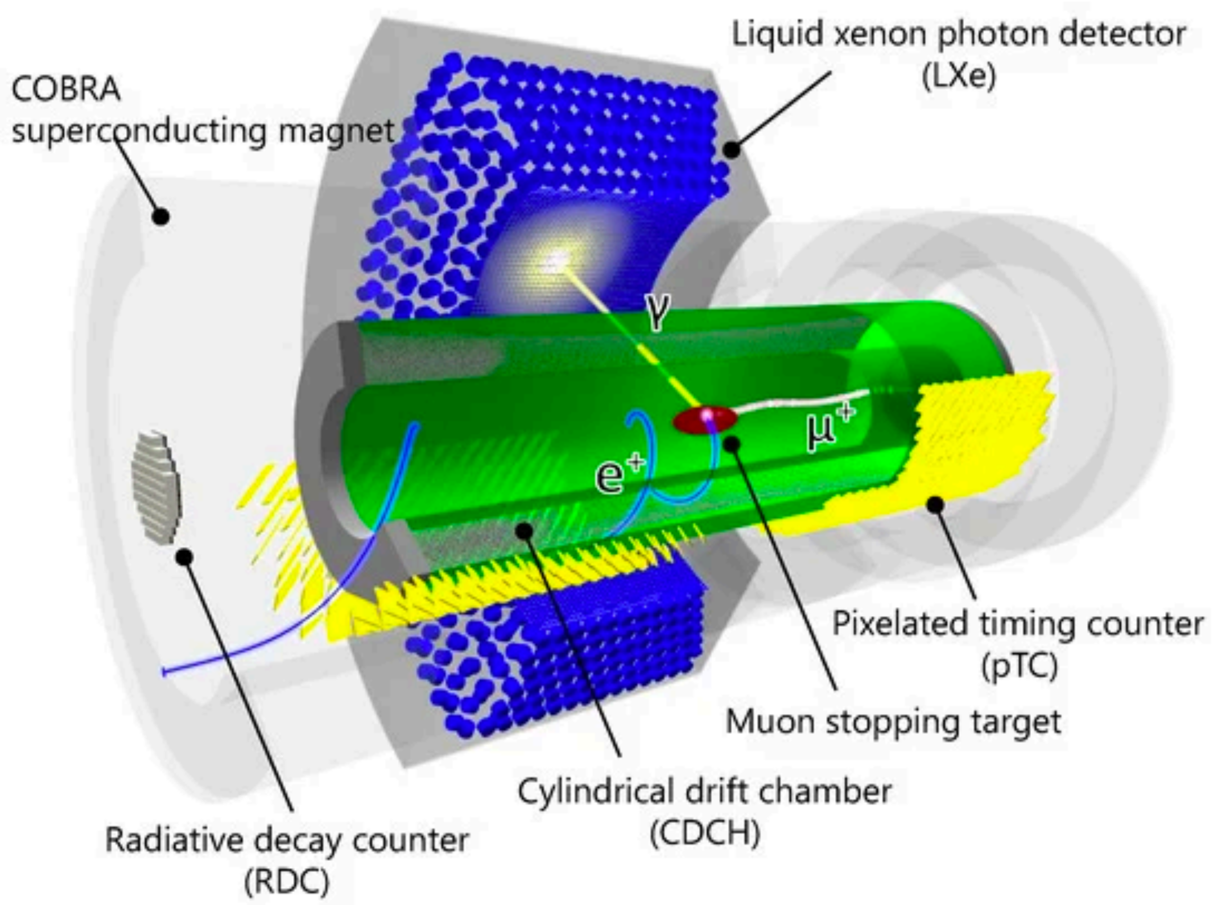
The UV models probed by these observables are related to NP at the TeV scale: (SUSY, Compositeness…)

L. Calibbi's talk this morning

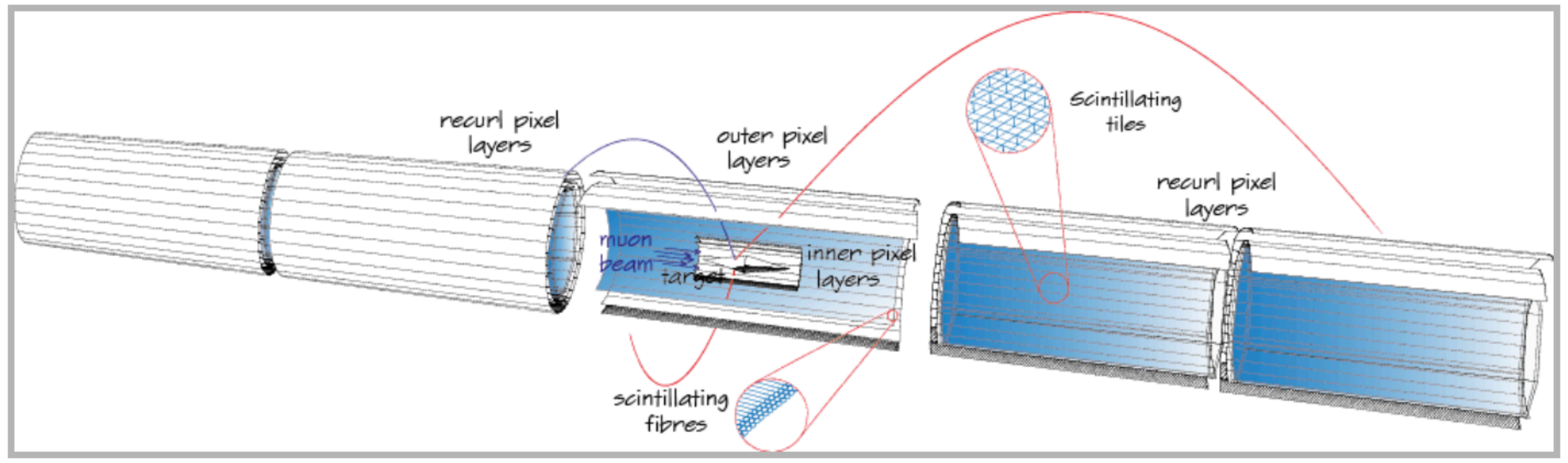
Heavy new physics experimental paradigm

MEG II



$$\mu^+ \to e^+\gamma$$

Mu3e



Schematic view of the planned Mu3e experiment

$$\mu^+ \to e^+e^-e^+$$

Signal characterised by **no missing energy**

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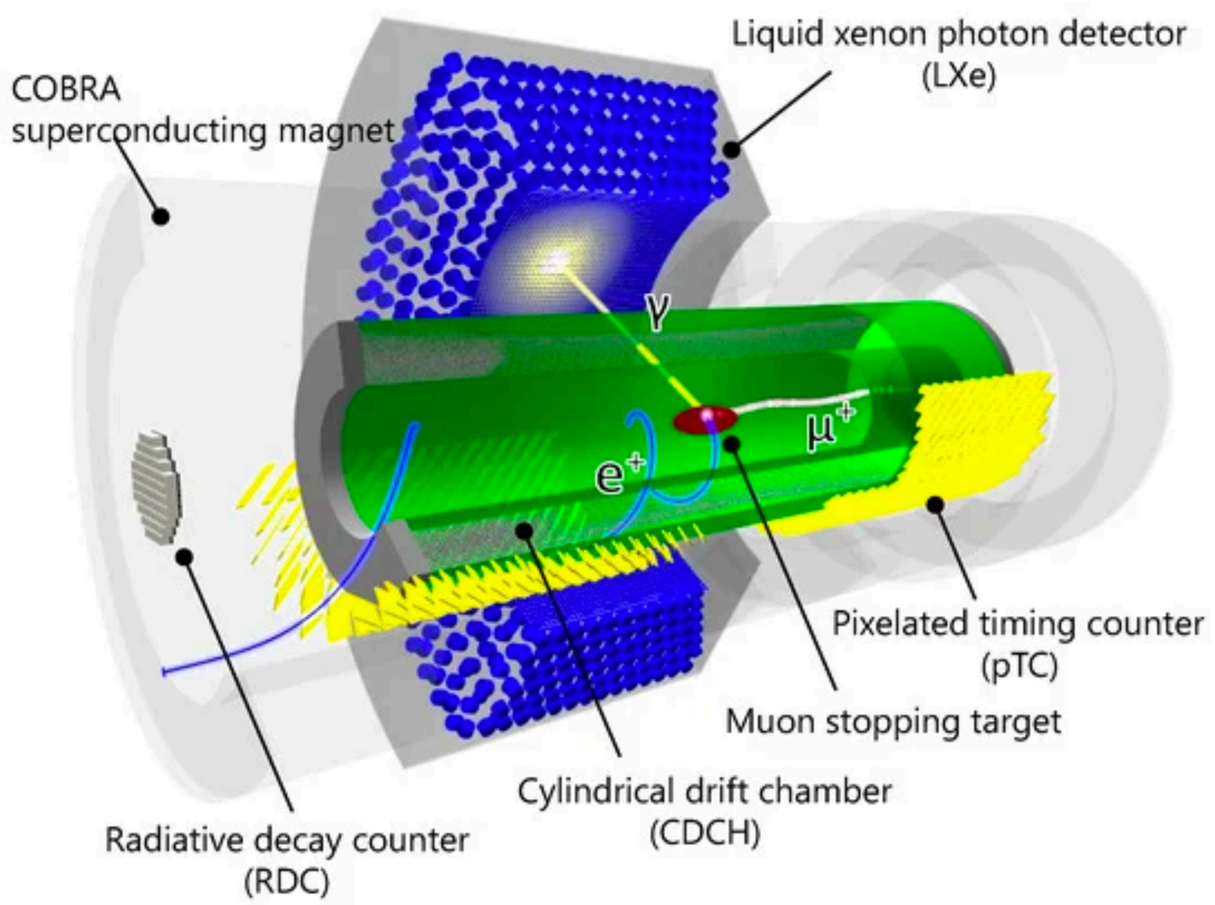

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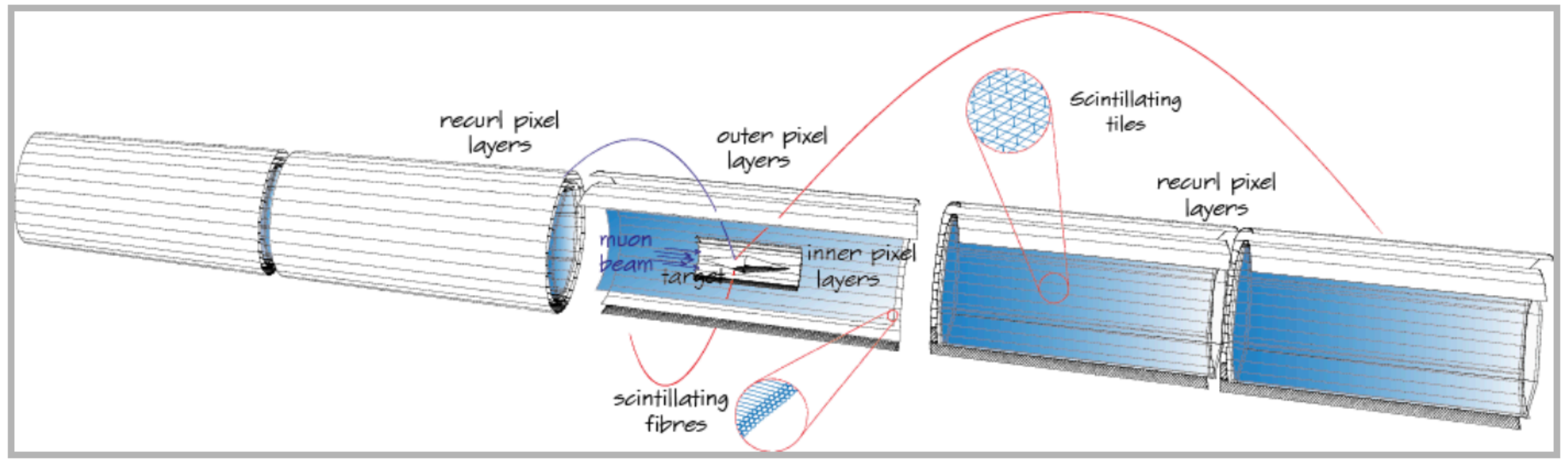


Schematic view of the planned Mu3e experiment

$$\mu^+ \to e^+e^-e^+$$

Signal characterised by **no missing energy**

The challenge is to **increase the luminosity** while suppressing coincidences
tightening the kinematic + timing requirements

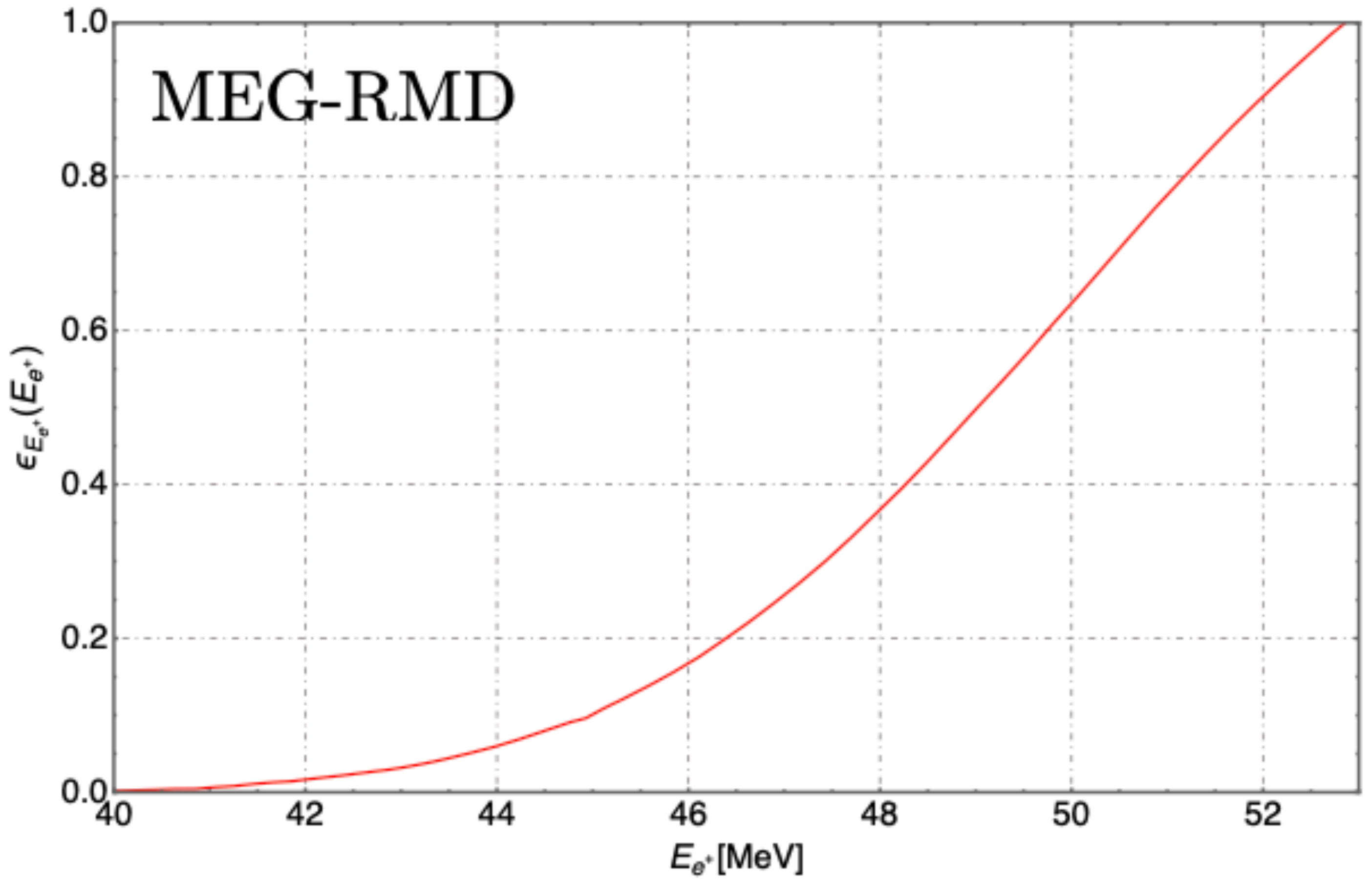
Example: trigger selection at MEG

$$\mu^+ \to e^+\gamma$$

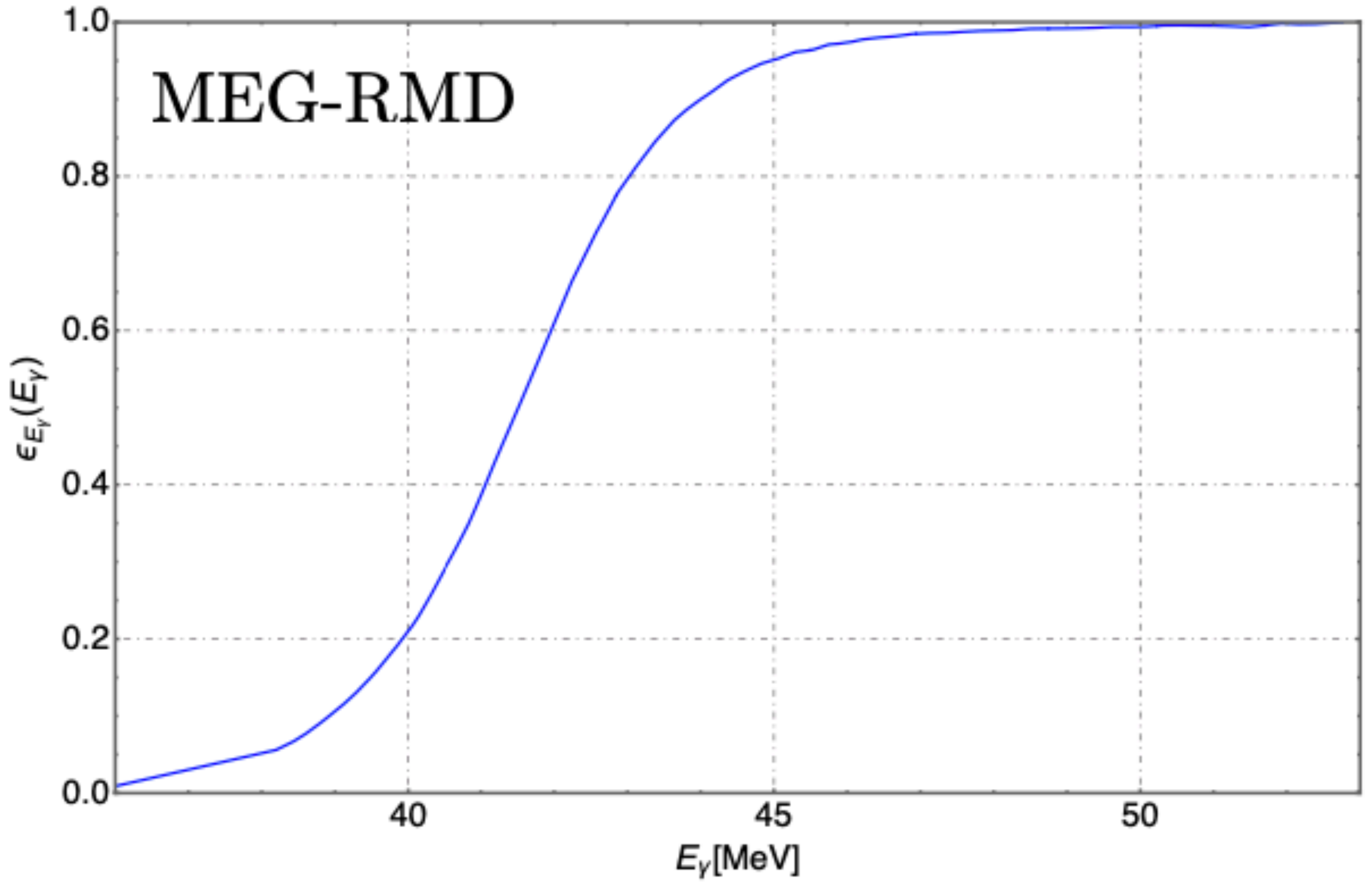
The trigger maximize the efficiency to back to back positron-photon of $E = m_\mu/2$

See Galli et al. *JINST 9 (2014)*

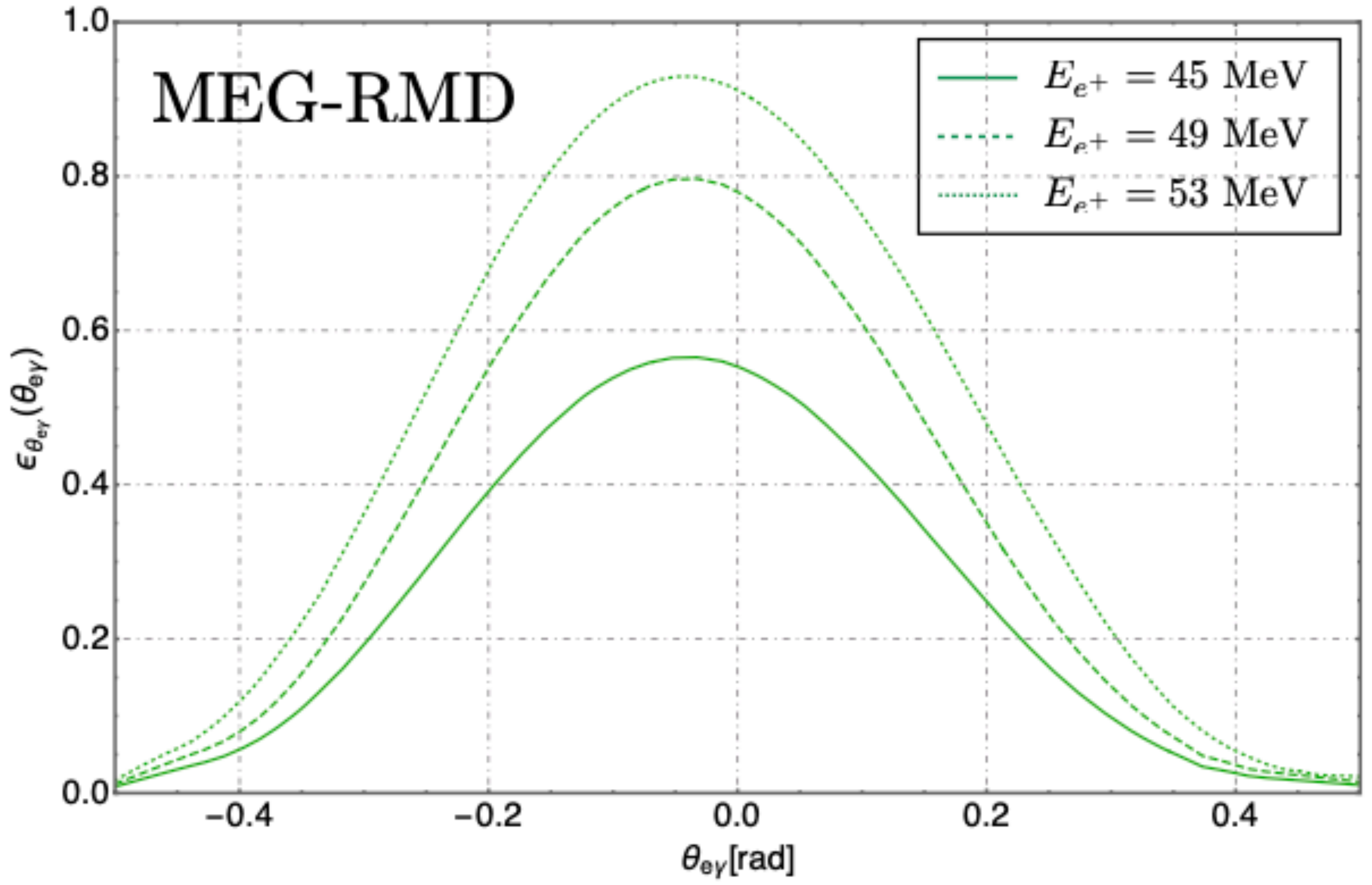
Positron energy >45 MeV @ hardware level



Photon >45 MeV @ trigger level



back to back topology @ trigger level



Taken from *MEG-RMD measurement 1312.3217*

Light new physics vs Lepton Flavor

Accidental symmetries of the Standard Model might be broken by light new particles feebly coupled to the SM

These light particles naturally emerges in models where Lepton Flavor is broken spontaneously at high scale (familon, axion, axion-like particles, majorons)

See. *L. Calibbi, D.R., R. Ziegler, J. Zupan 2006.04795*

Light pseudo-Goldstone bosons (or ALP) $m_a \ll m_\mu$

LFV @ dimension 5

$$\mathcal{L}_{\rm eff}^{\rm LFV} \supset \frac{\partial_\mu a}{2 f_a} \bar{\mu}\gamma^\mu (C^V_{\mu e} + C^A_{\mu e}\gamma_5) e + \frac{\partial_\mu a}{f_a} \bar{e}\gamma^\mu\gamma_5 e + \frac{m_a^2}{2} a^2 + \frac{1}{f_a^2} \cdots$$

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$$c\tau \sim \frac{8\pi f_a^2}{m_a^3} \gg L_{\text{detector}}$$

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Interplay between flavor experiments and astrophysics

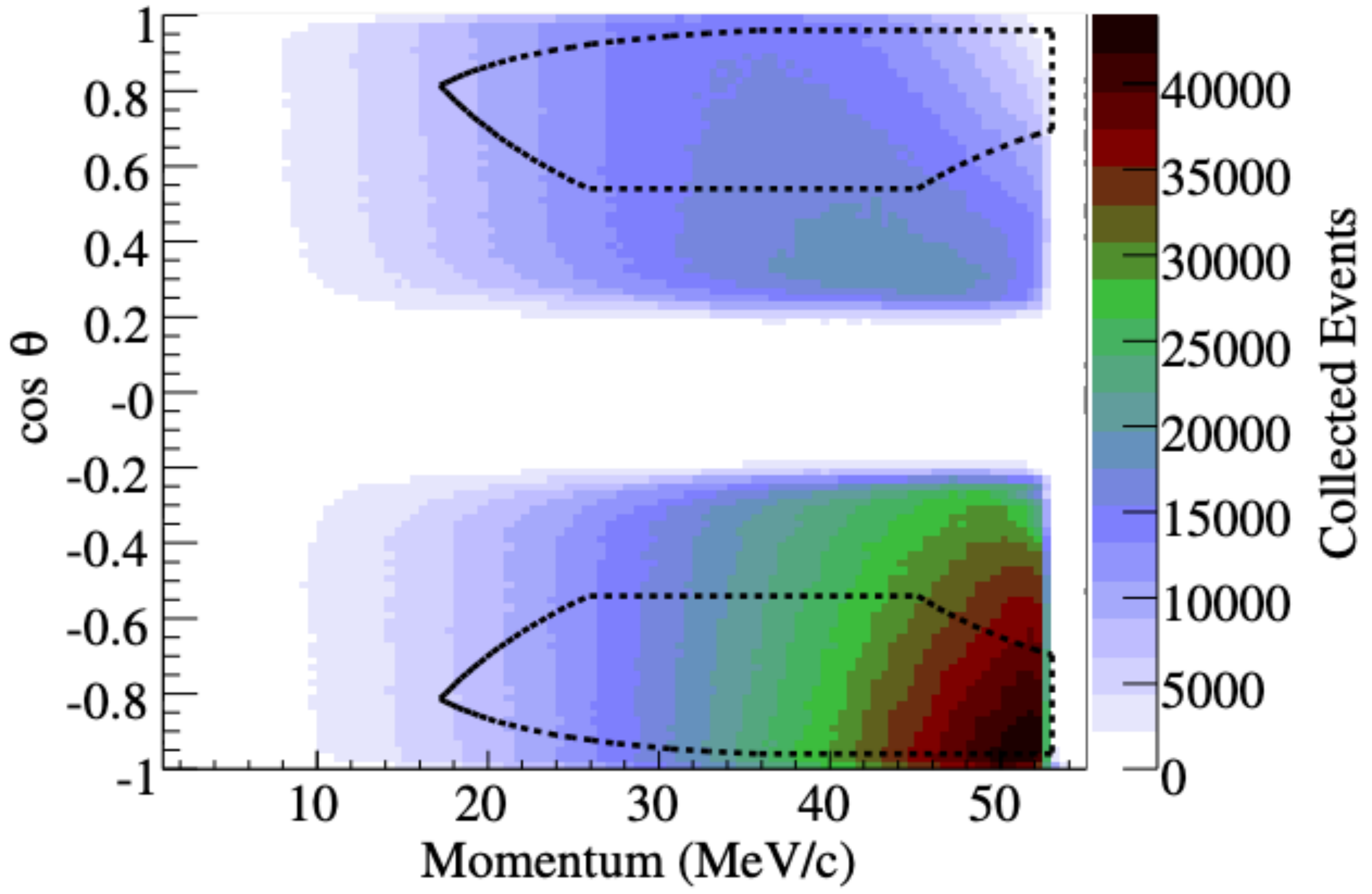
Light new physics experimental paradigm

Hunt for rare muon decays with missing energy

$\mu \to ea$

Huge irreducible background from Michel $\mu \to e\nu\bar{\nu}$

See. *TWIST 1409.0638*



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Muon polarization can help discriminating the signal

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bkd suppressed in the fwd region

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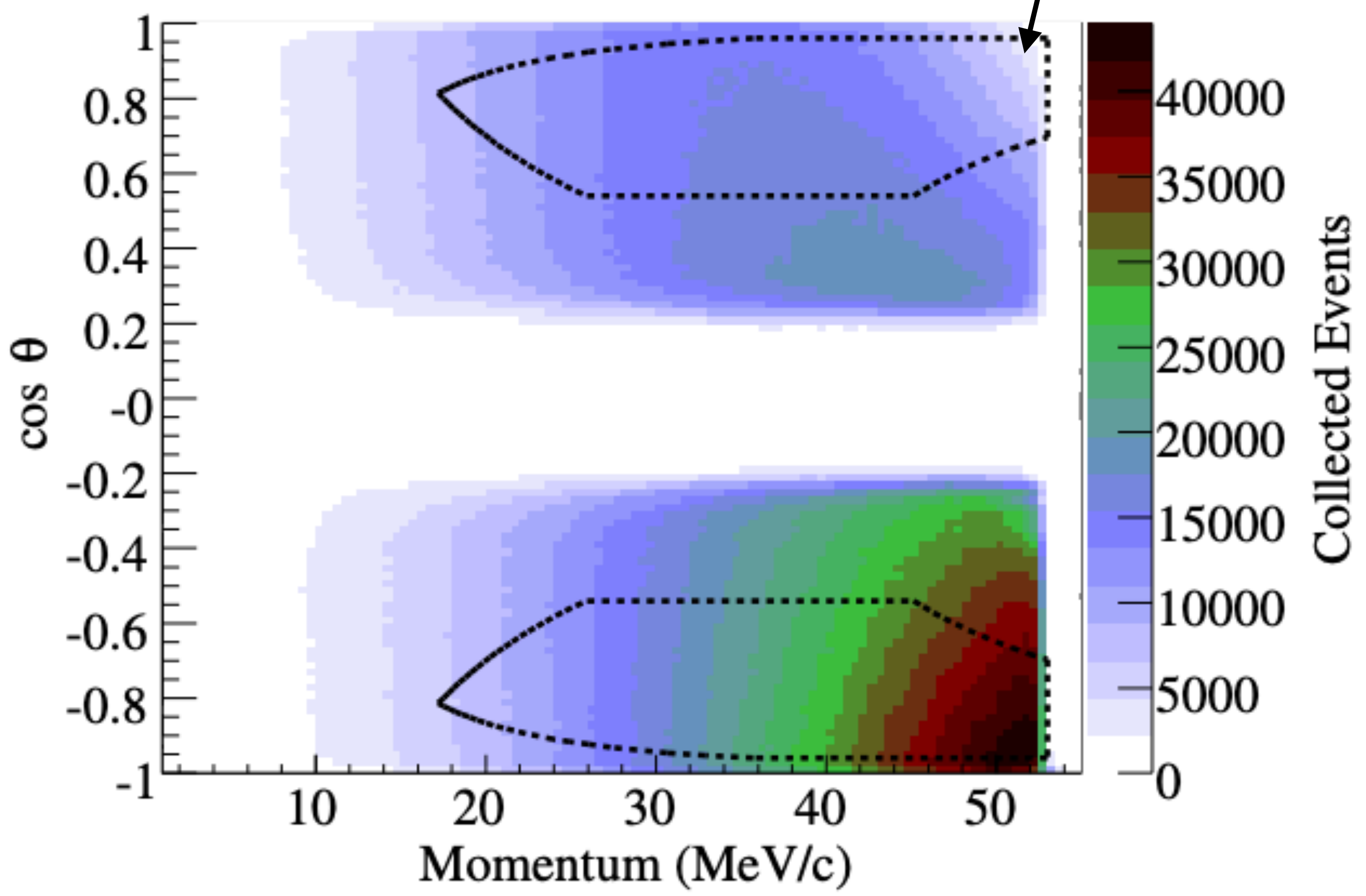

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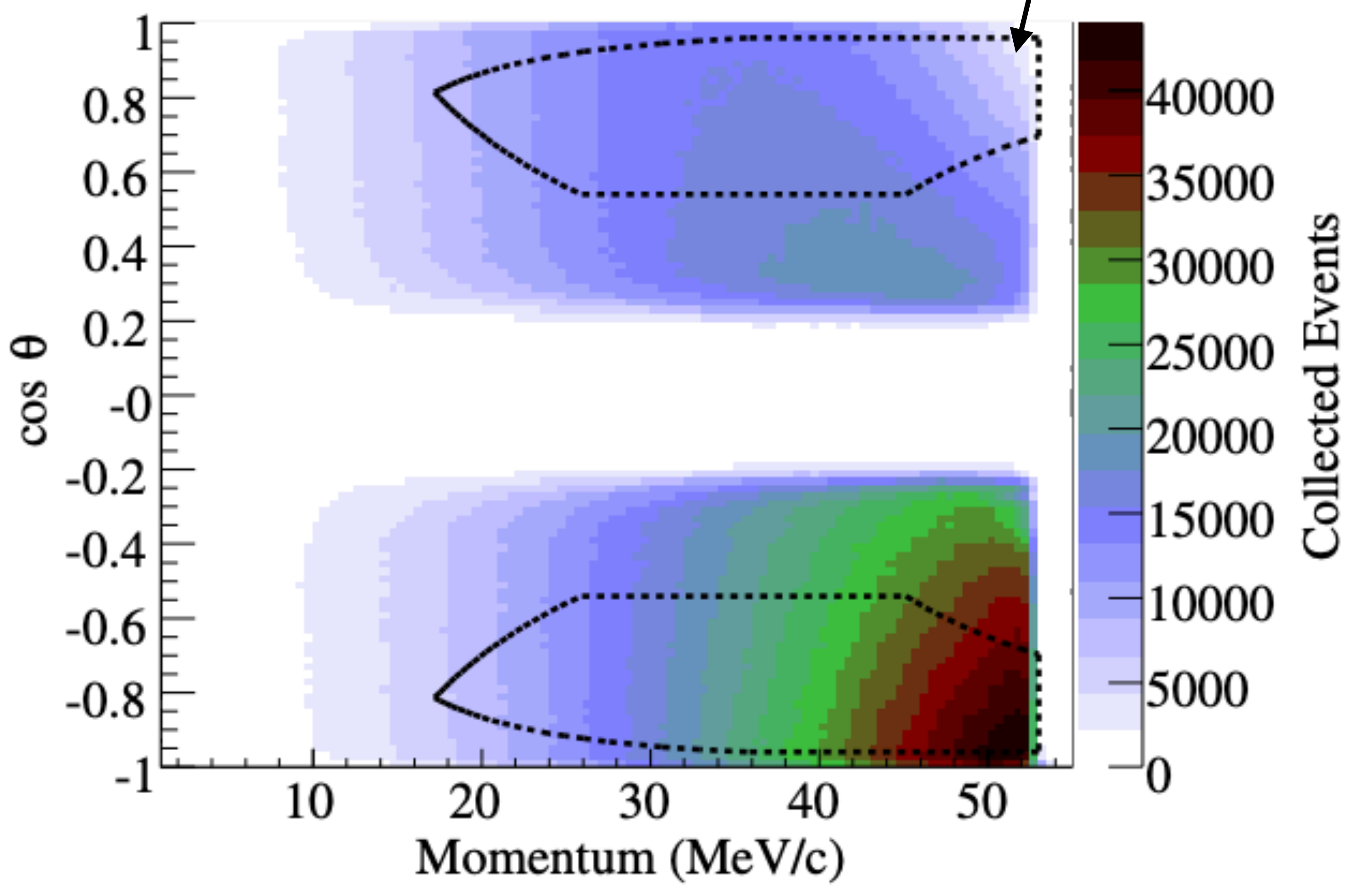

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The extra photon helps constructing a missing mass distribution which is not used for calibration

The price to pay is a reduced signal by $\sim \frac{\alpha}{2\pi} \log \frac{2E_\gamma}{m_\mu}$

See. *S. Knapen and Y. Jho 2203.11222*

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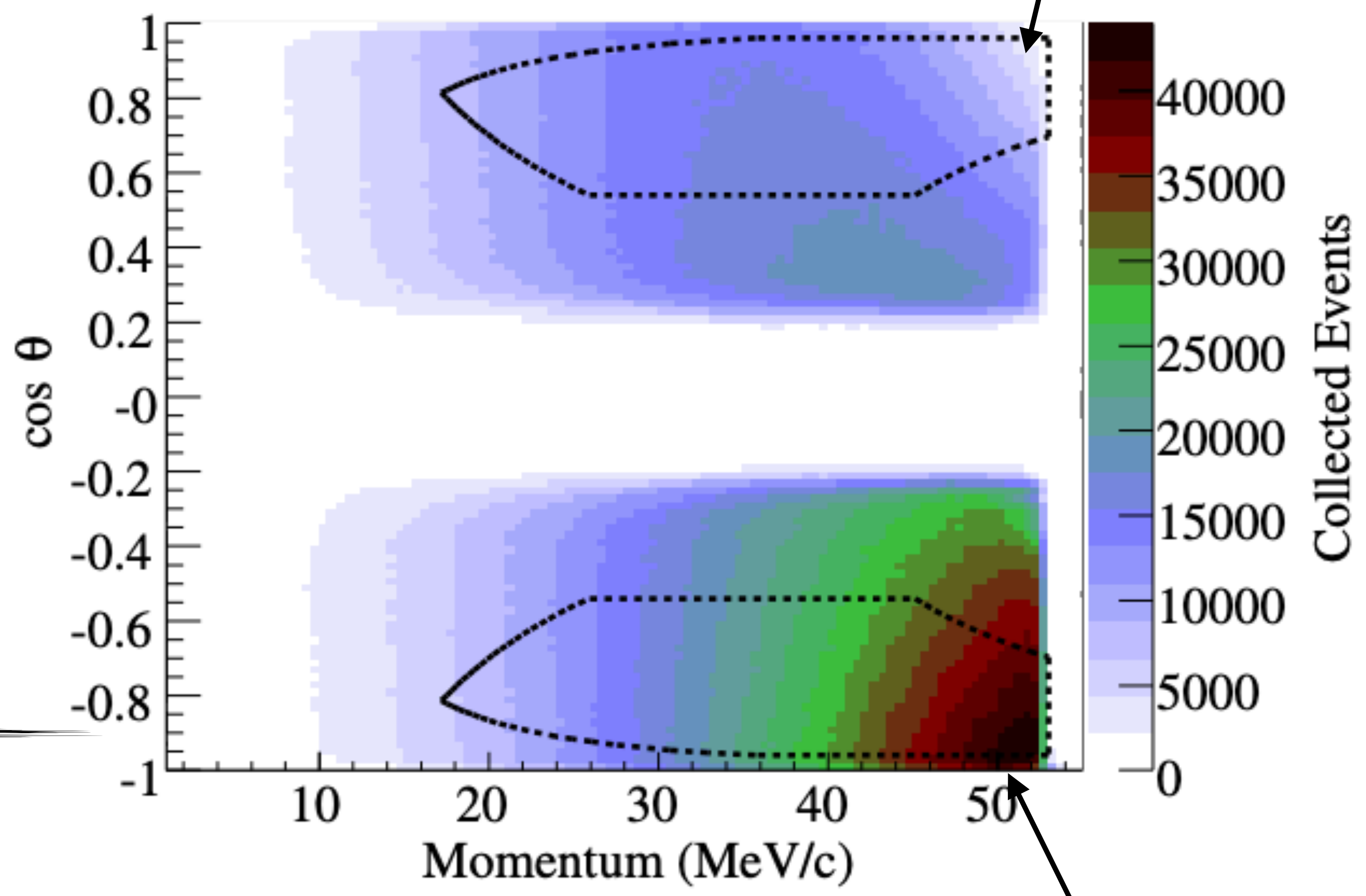
For left-handed couplings the limitation are large systematics

bkd suppressed in the fwd region

See. *TWIST 1409.0638*



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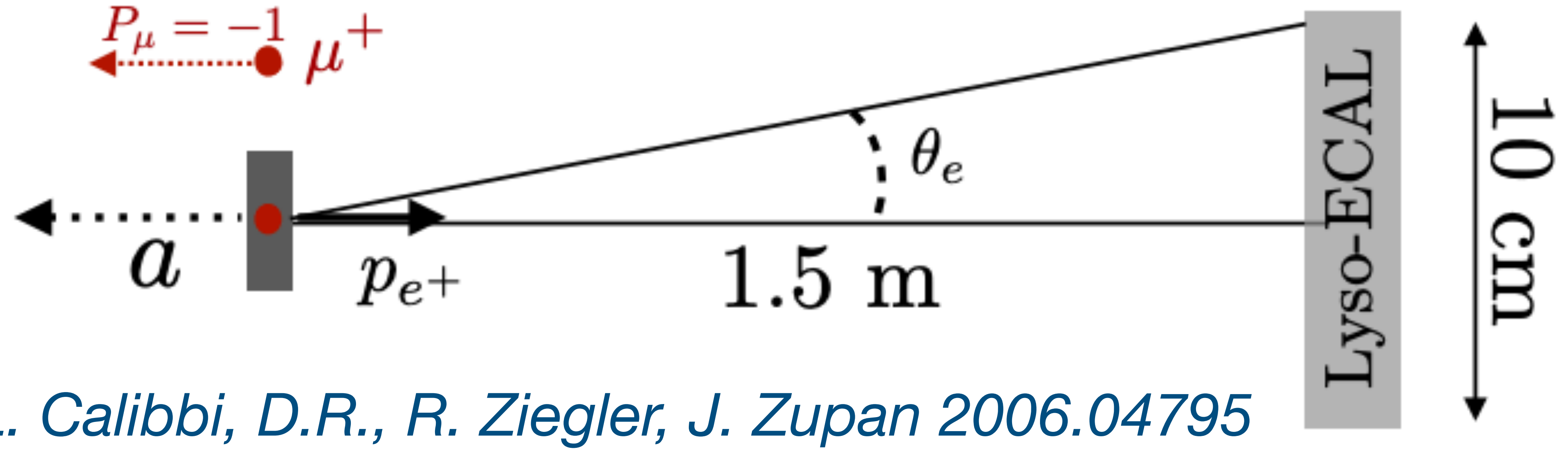
Looking forward for right-handed ALPs



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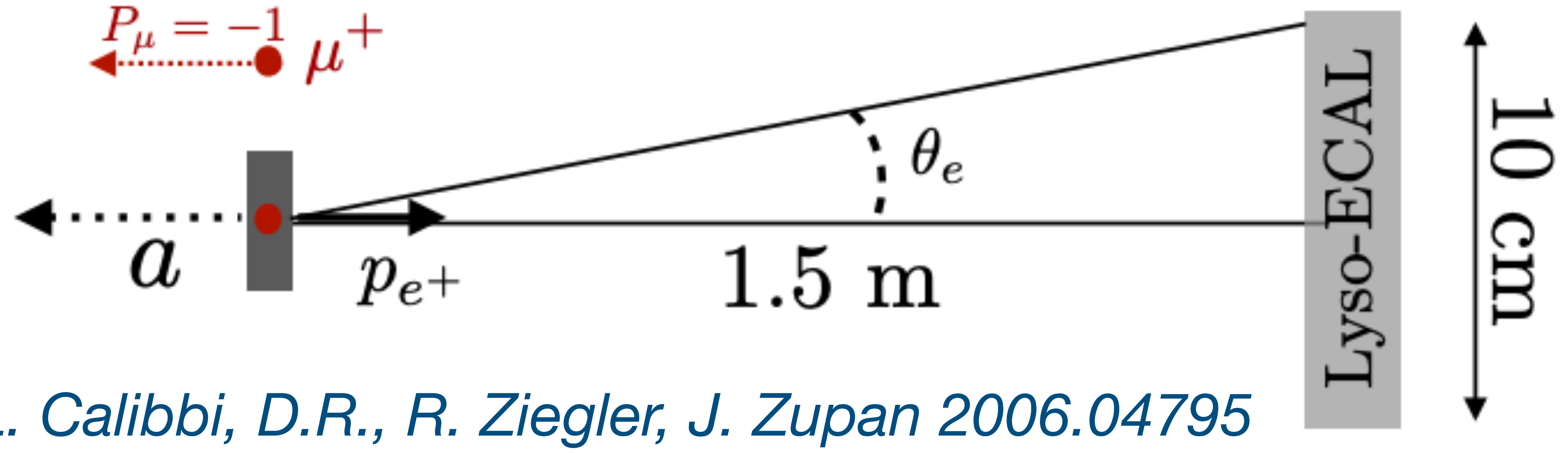

L. Calibbi, D.R., R. Ziegler, J. Zupan 2006.04795

Background suppression in the fwd direction requires:

1) good momentum resolution $\delta x_e \sim \%$

2) purely polarized muon beam $\delta P_\mu \sim 10^{-2}$

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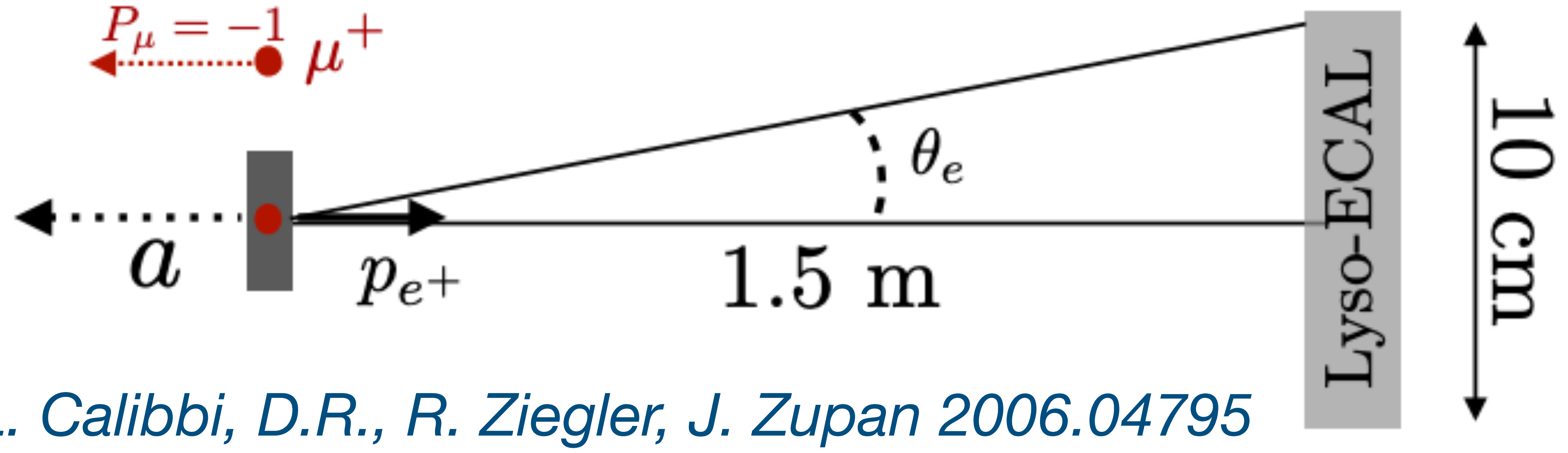

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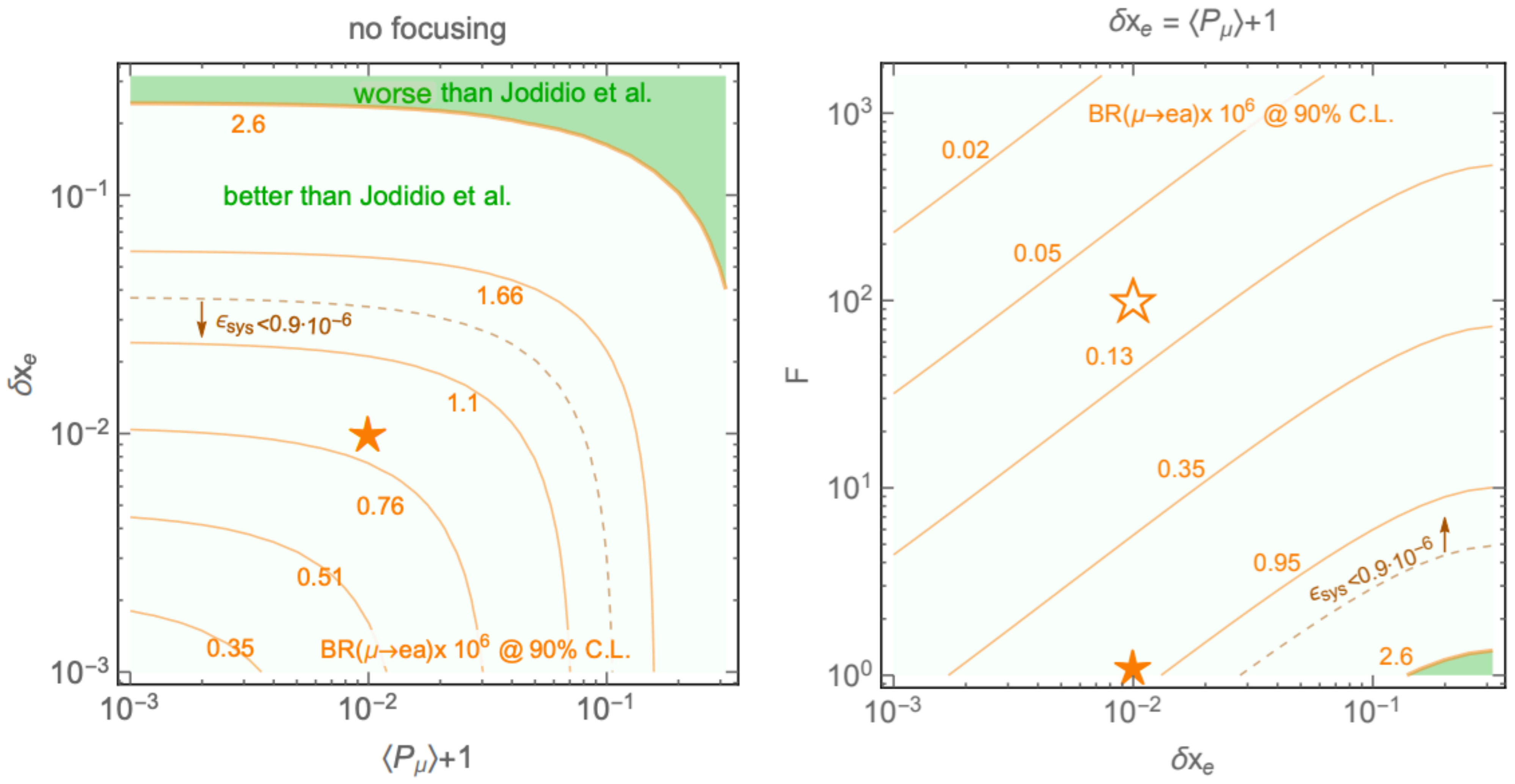

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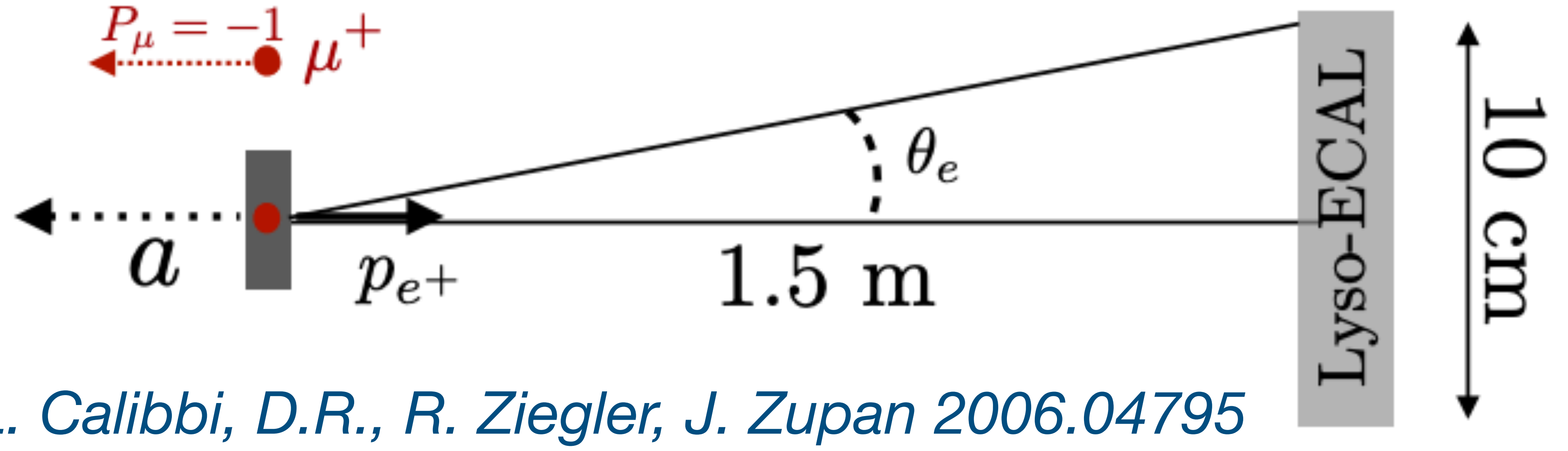

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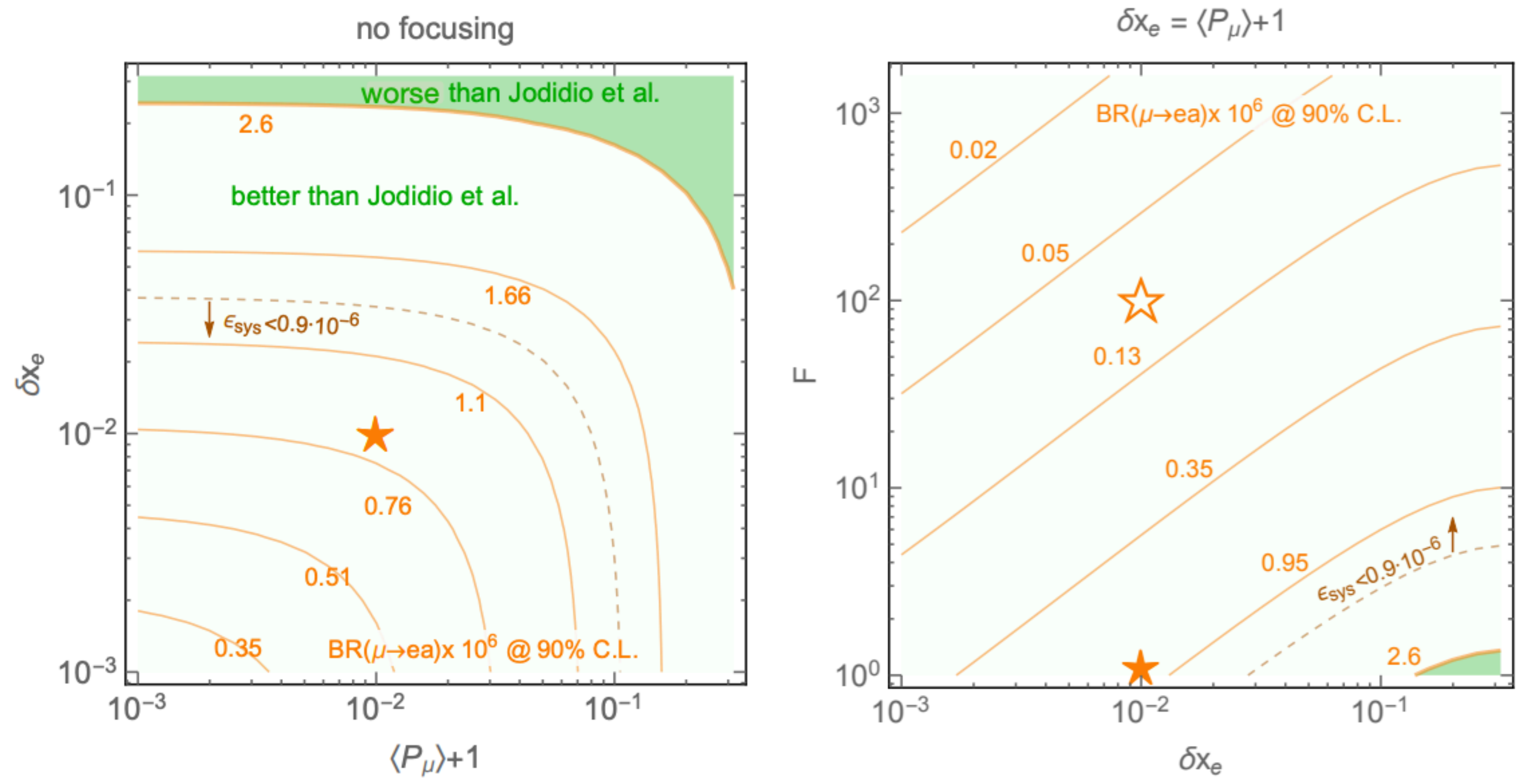

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4) large luminosity $N_\mu \sim 10^{14} \mu^+$
5) very low systematics

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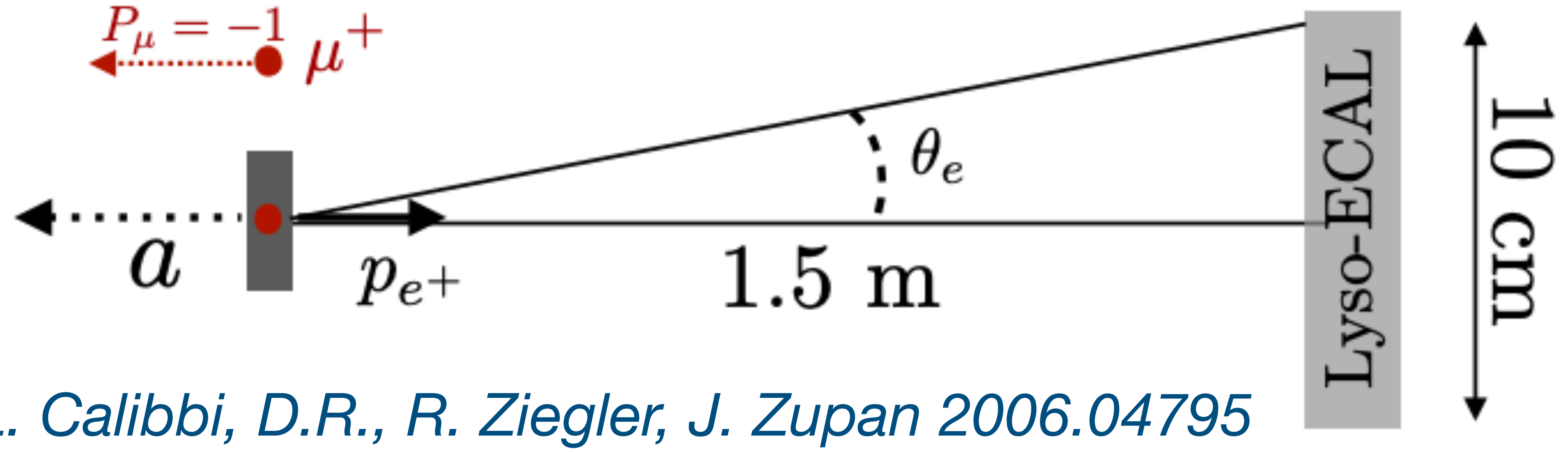

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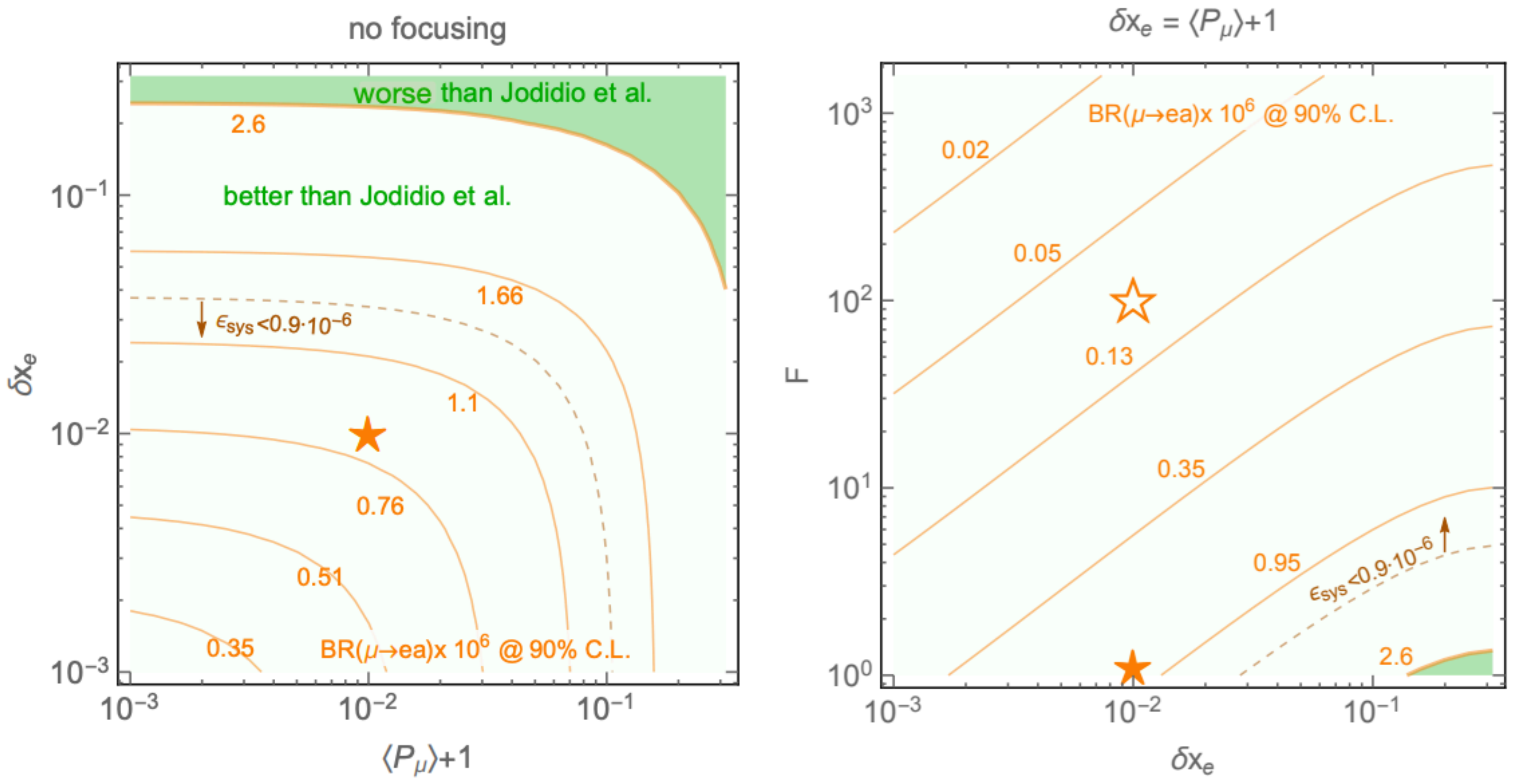

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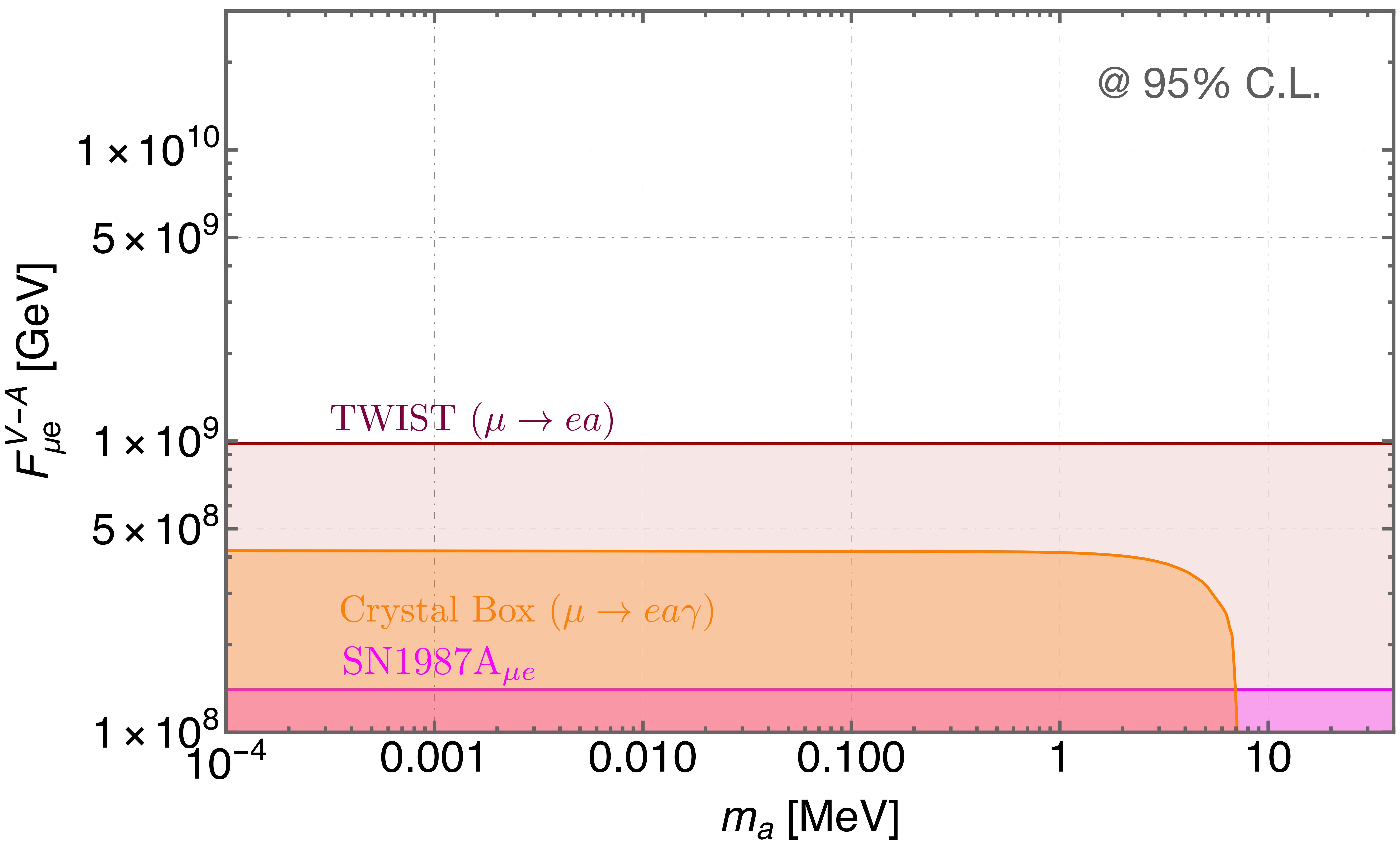
These conditions have been realized before in the Iodidio's exp.

Iodidio et al. (1986)

Can it be done again?

STATUS for left-handed LFV ALP



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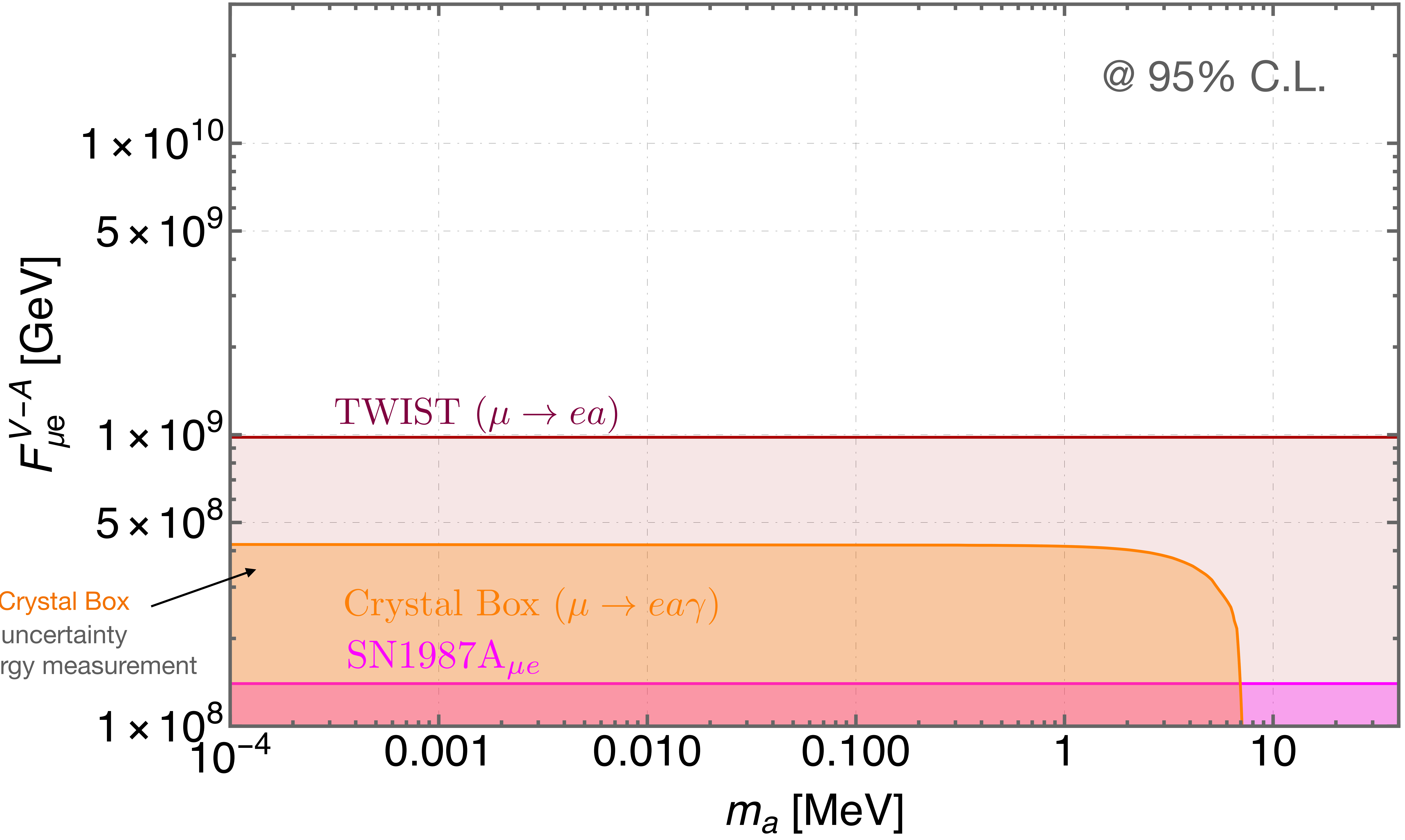

Bound from Crystal Box suffers from uncertainty in the positron energy measurement

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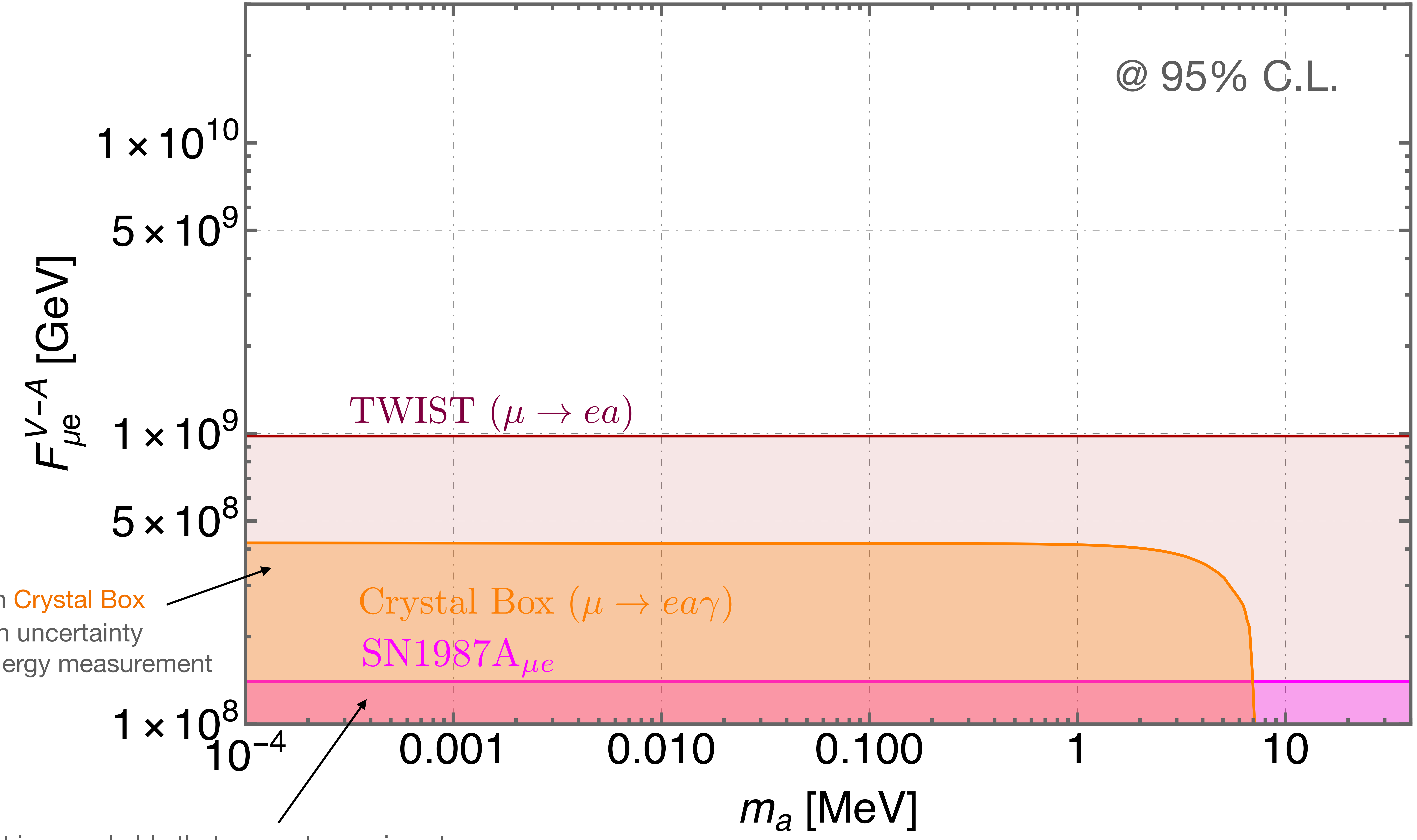

Bound from Crystal Box suffers from uncertainty in the positron energy measurement

It is remarkable that present experiments are already stronger than cooling bounds!

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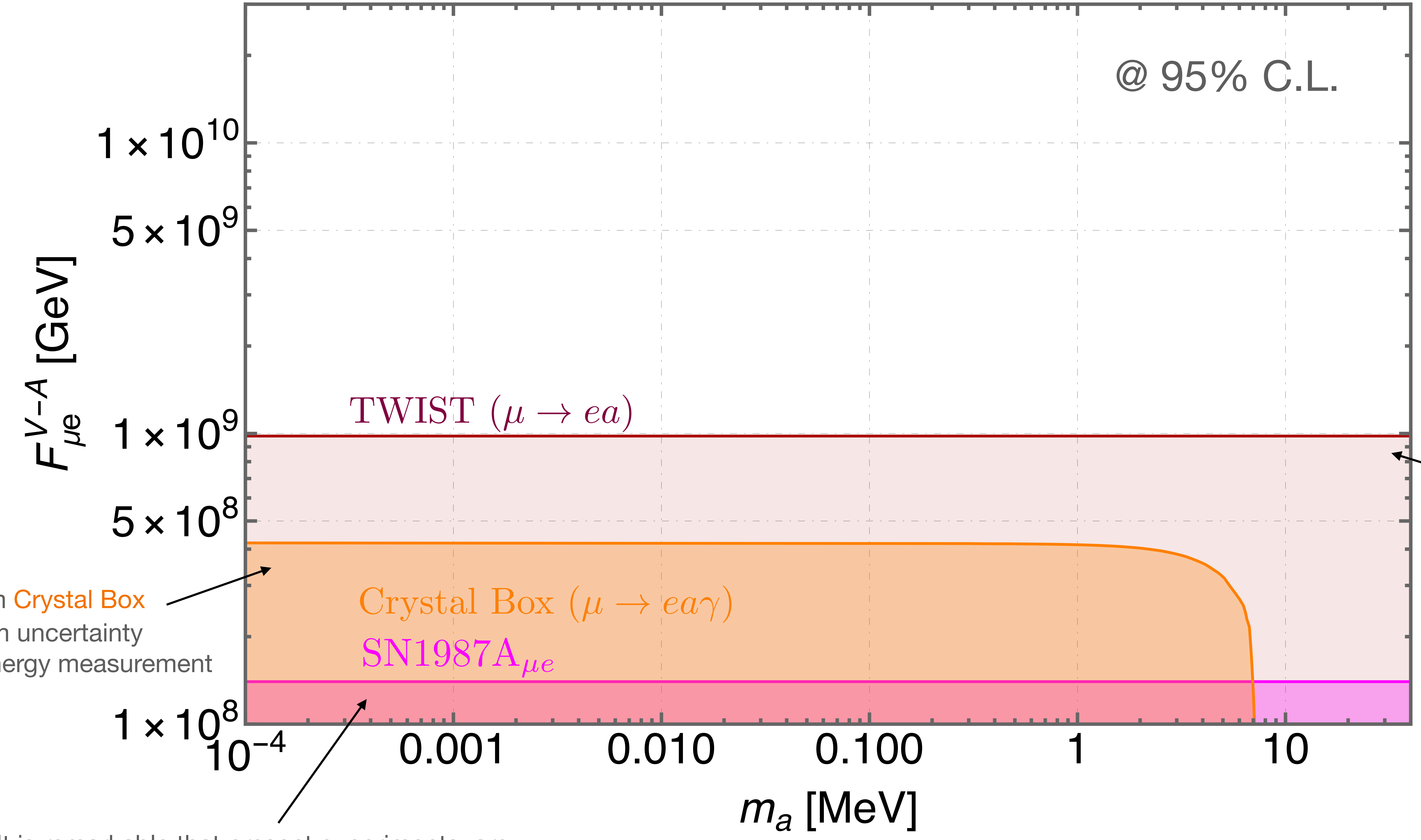


Bound from Crystal Box suffers from uncertainty in the positron energy measurement

TWIST bound suffers from large systematic uncertainties

See. *TWIST 1409.0638*

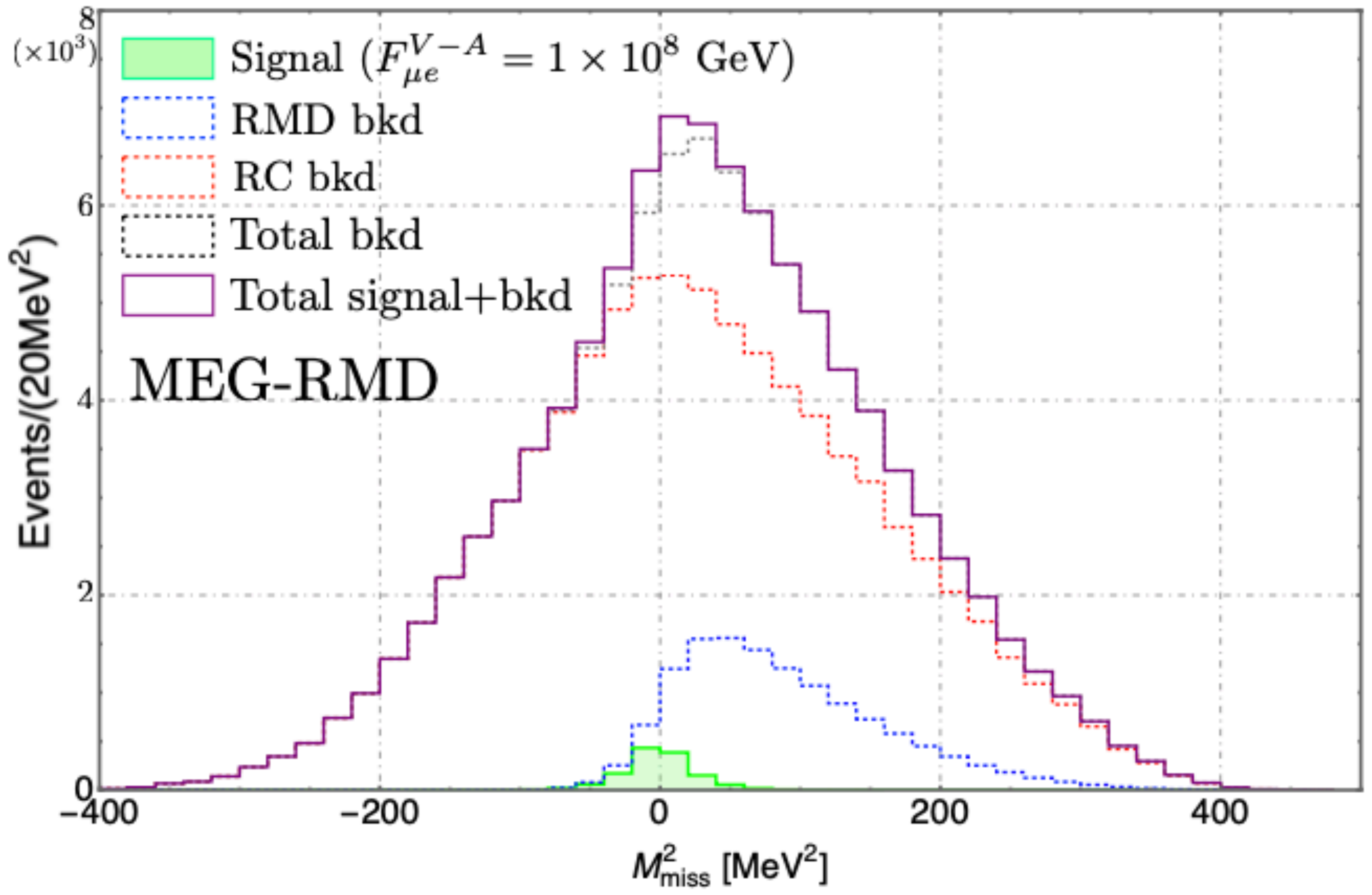
It is remarkable that present experiments are already stronger than cooling bounds!

What MEG can teach us about LFV axions?

MEG-RMD search *1312.3217* $N_\mu = 1.8 \times 10^{14}$ collected in 2009-2010

The goal was to observe the RMD $\mu \to e\nu\bar{\nu}\gamma$

over the bkd of random coincidences (RC): pileup of $\mu \to e\nu\bar{\nu}\gamma \; + \; \mu \to e\nu\bar{\nu}$



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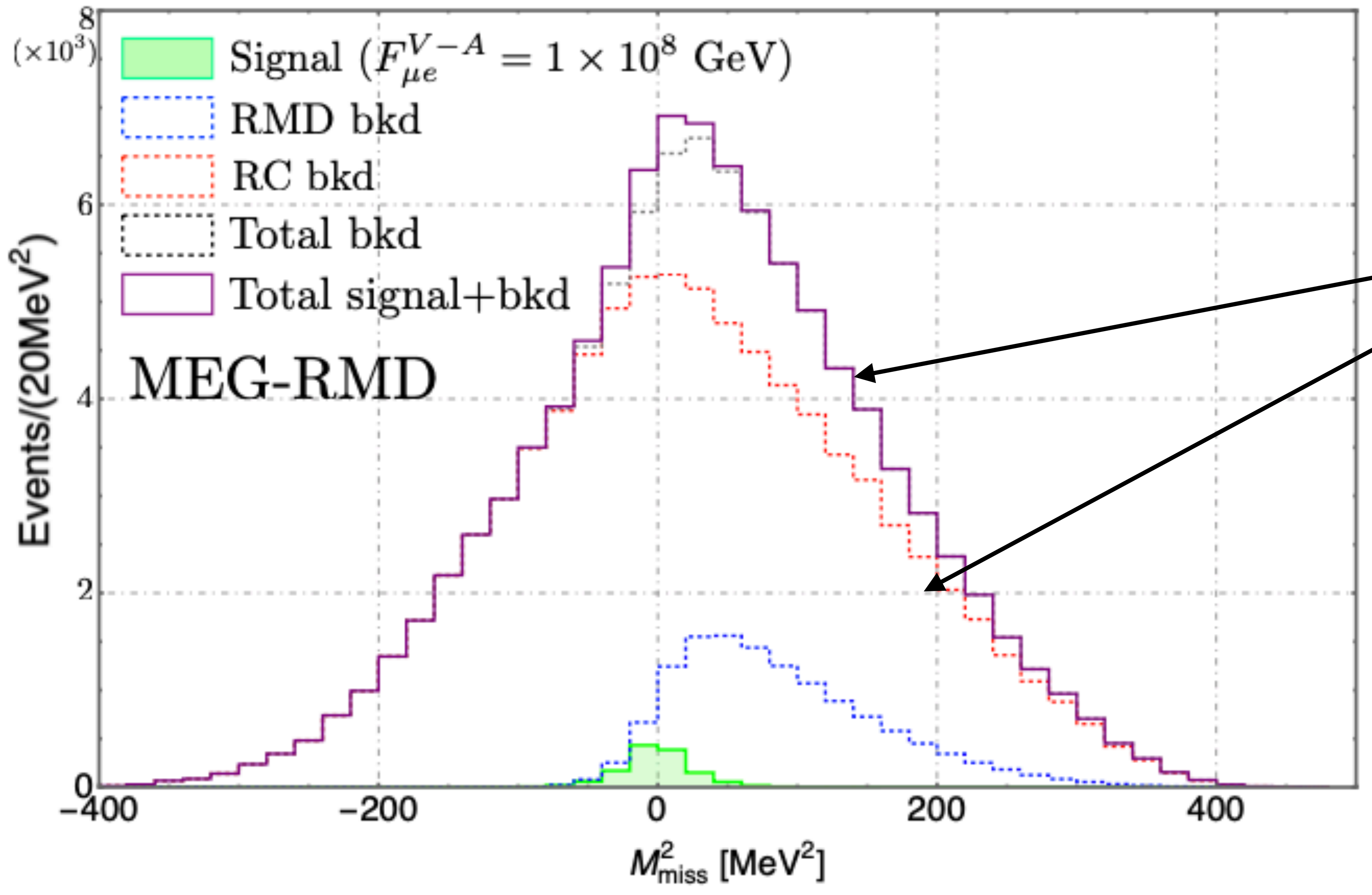

missing mass distribution of the bkd obtained with an home brew MC normalized to the offline number of RMD and RC events observed.

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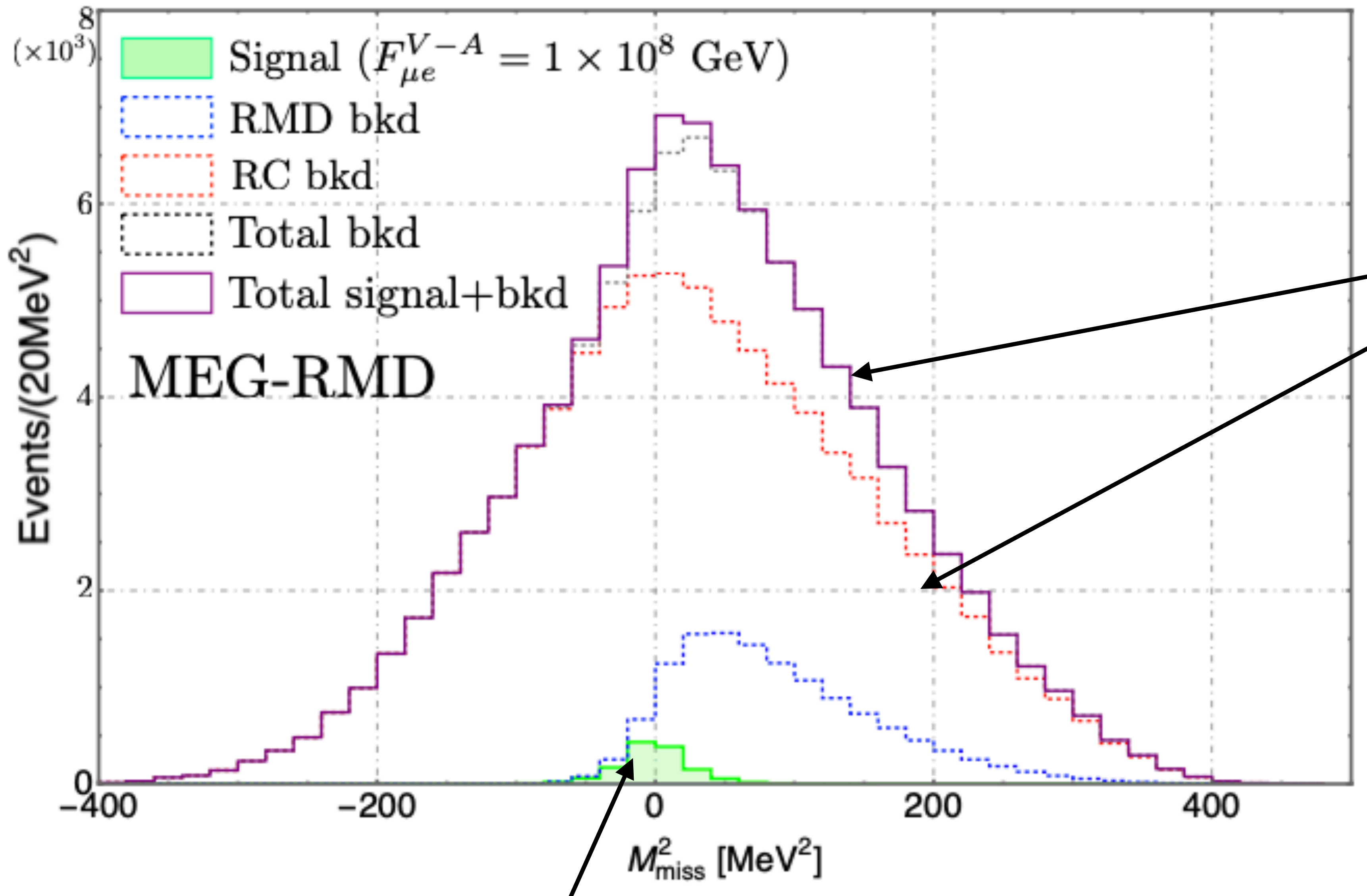


missing mass distribution of the bkd obtained with an home brew MC normalized to the offline number of RMD and RC events observed.

Signal with a rate $\mu \to e a\gamma$ with mu polarisation

See. *MEG 1510.04743* with mu polarisation

$$\langle P_\mu \rangle = -0.856 \pm 0.021$$

We account for detector smearing

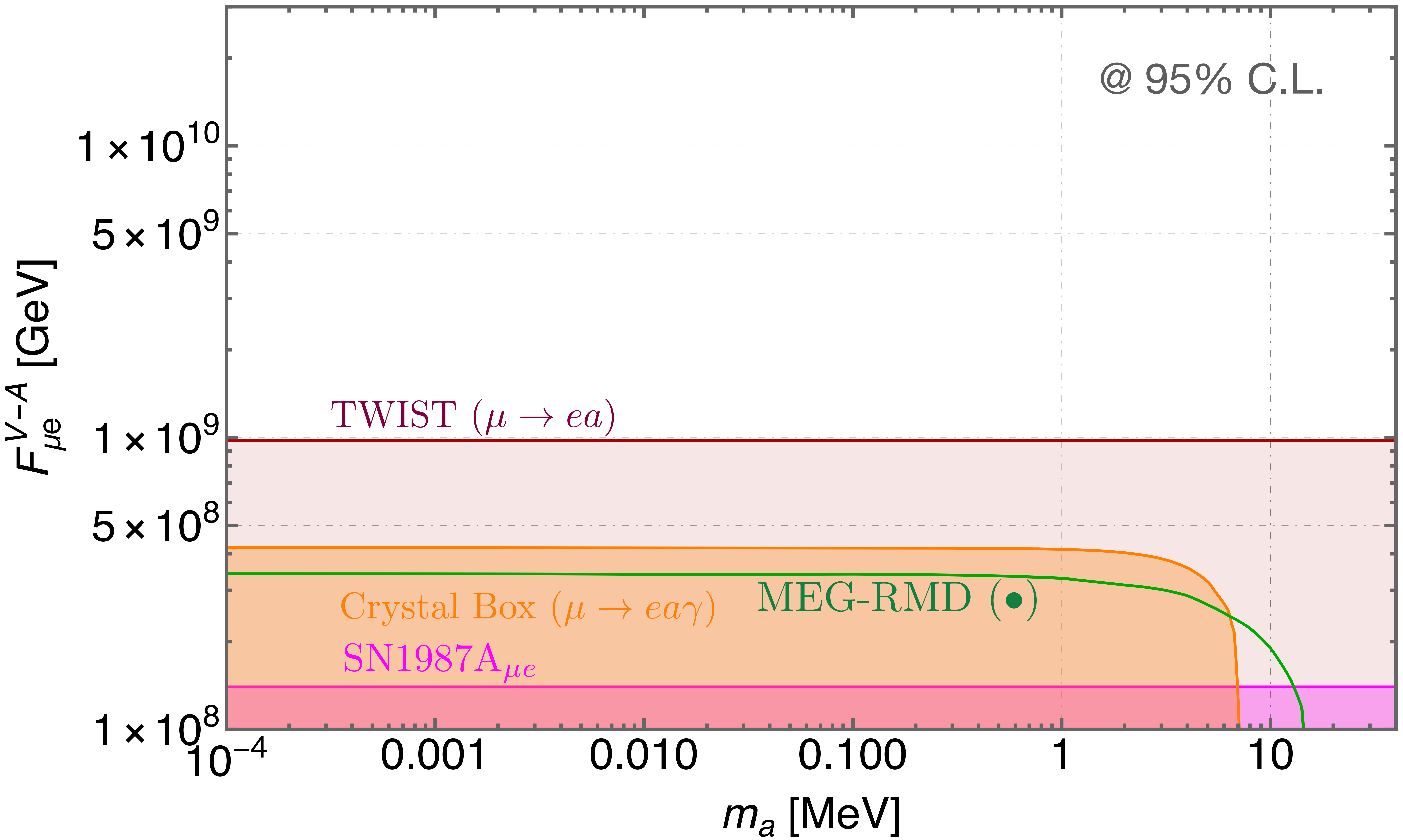
See. *MEG 2005.00339*

What MEG can teach us about LFV axions?

with $N_\mu = 1.8 \times 10^{14}$ collected in 2009-2010

The topology is already close to back to back at trigger level

Very low signal efficiency for $\mu \to ea\gamma$ limits the MEG reach



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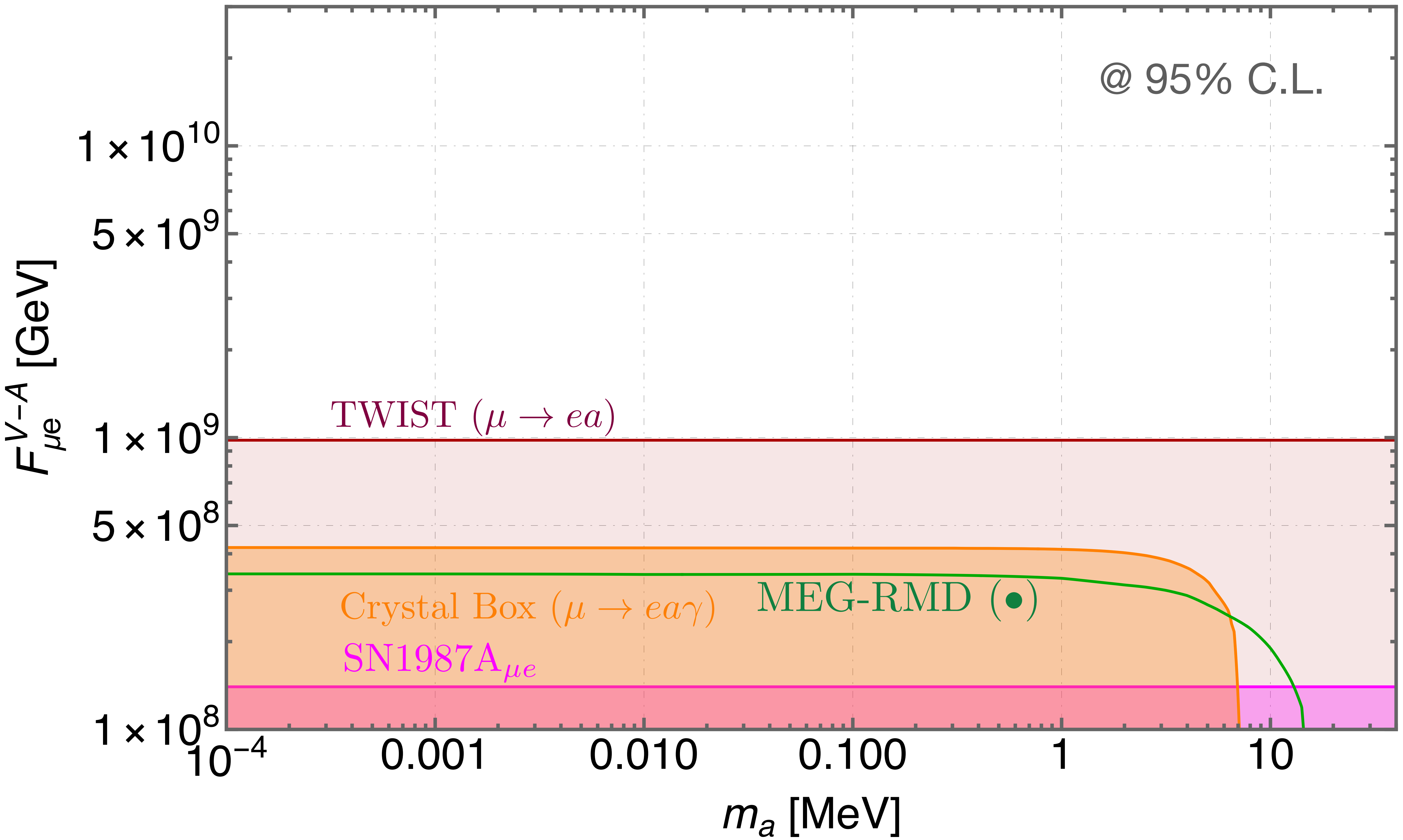

	$\mathrm{BR}_i^{\mathrm{base}}$	$\epsilon_i^{\mathrm{trig.}}$		
		ϵ_{E_e}	ϵ_{E_γ}	$\epsilon_{\theta_{e\gamma}}$
$\mathcal{B}_{\mathrm{RMD}}$	1.44×10^{-5}	0.15	5.3×10^{-4}	0.49
$\mathcal{B}_{\mathrm{RC}}$	7.08×10^{-4}	0.34	0.01	0.03

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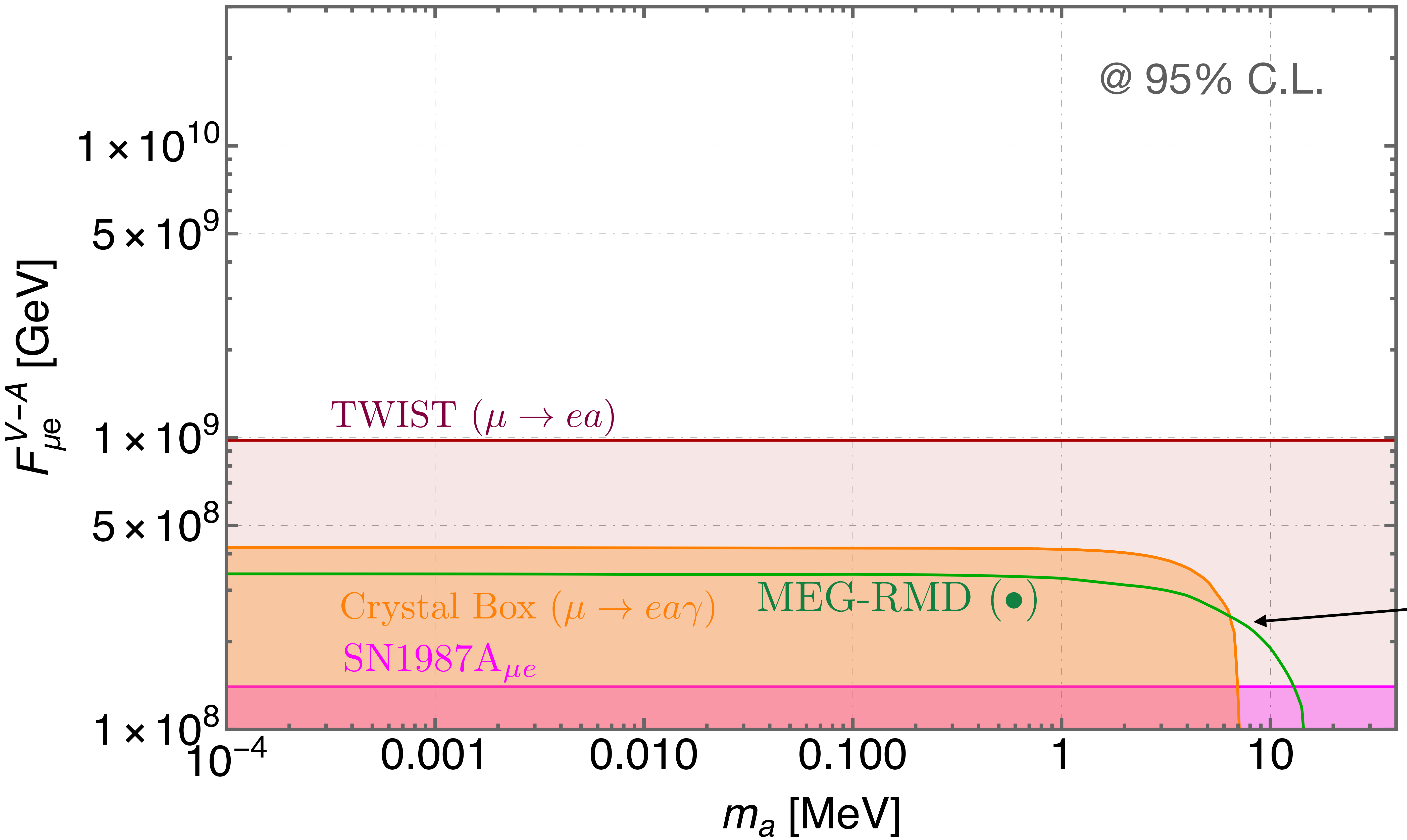

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3×10^{-4}

MEG RMD data expected sensitivity is already comparable to Crystal Box!

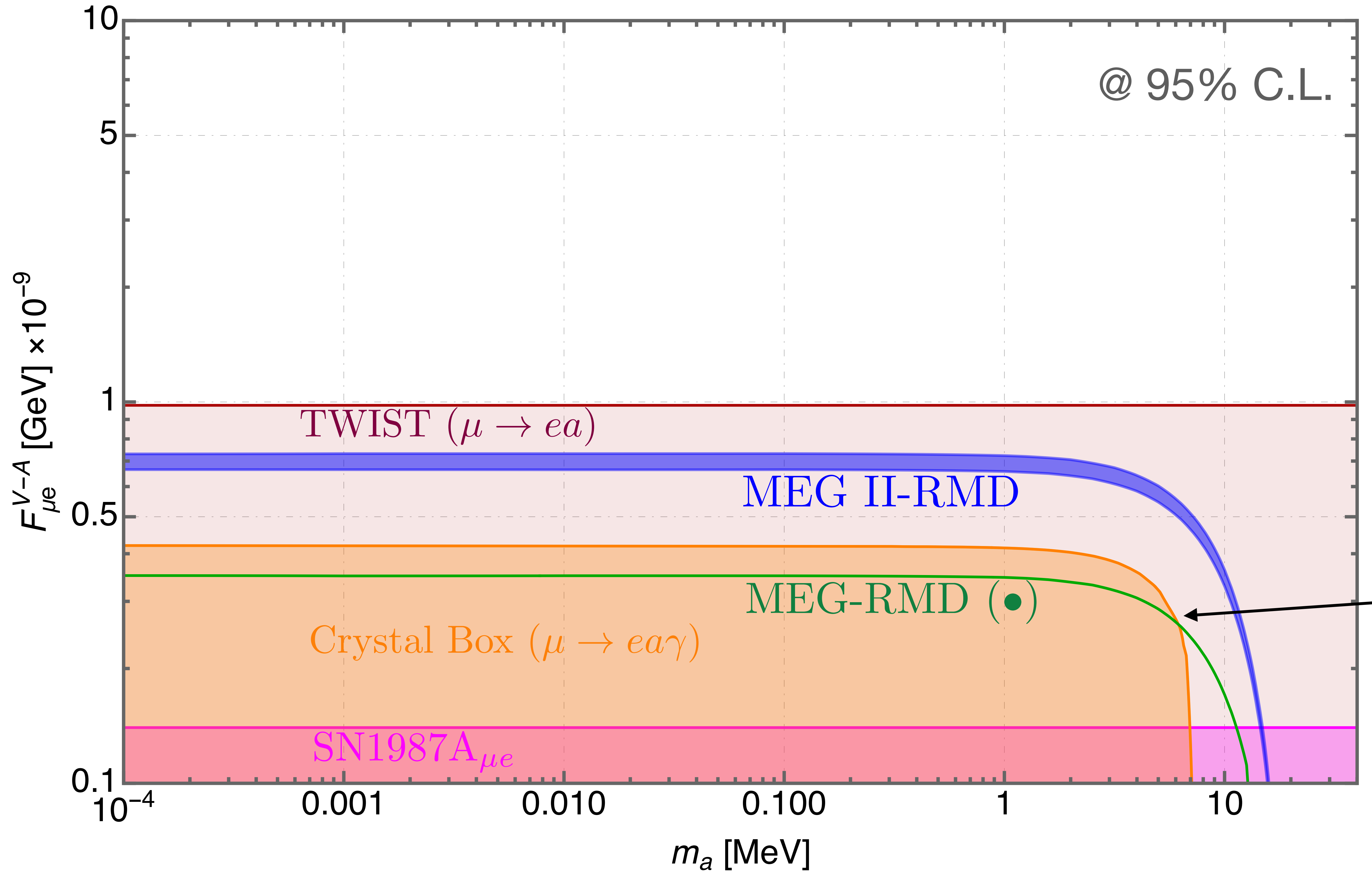
What about MEG II?

Keeping the same analysis as the MEG-RMD one but accounting for:

1) larger luminosity $N_\mu = 1.8 \times 10^{15} \mu^+$

2) Improved energy and angular resolution See *MEG II 1801.04688*

3) Reduced RC background by 50% after installation of radiative decay counter (RDC)



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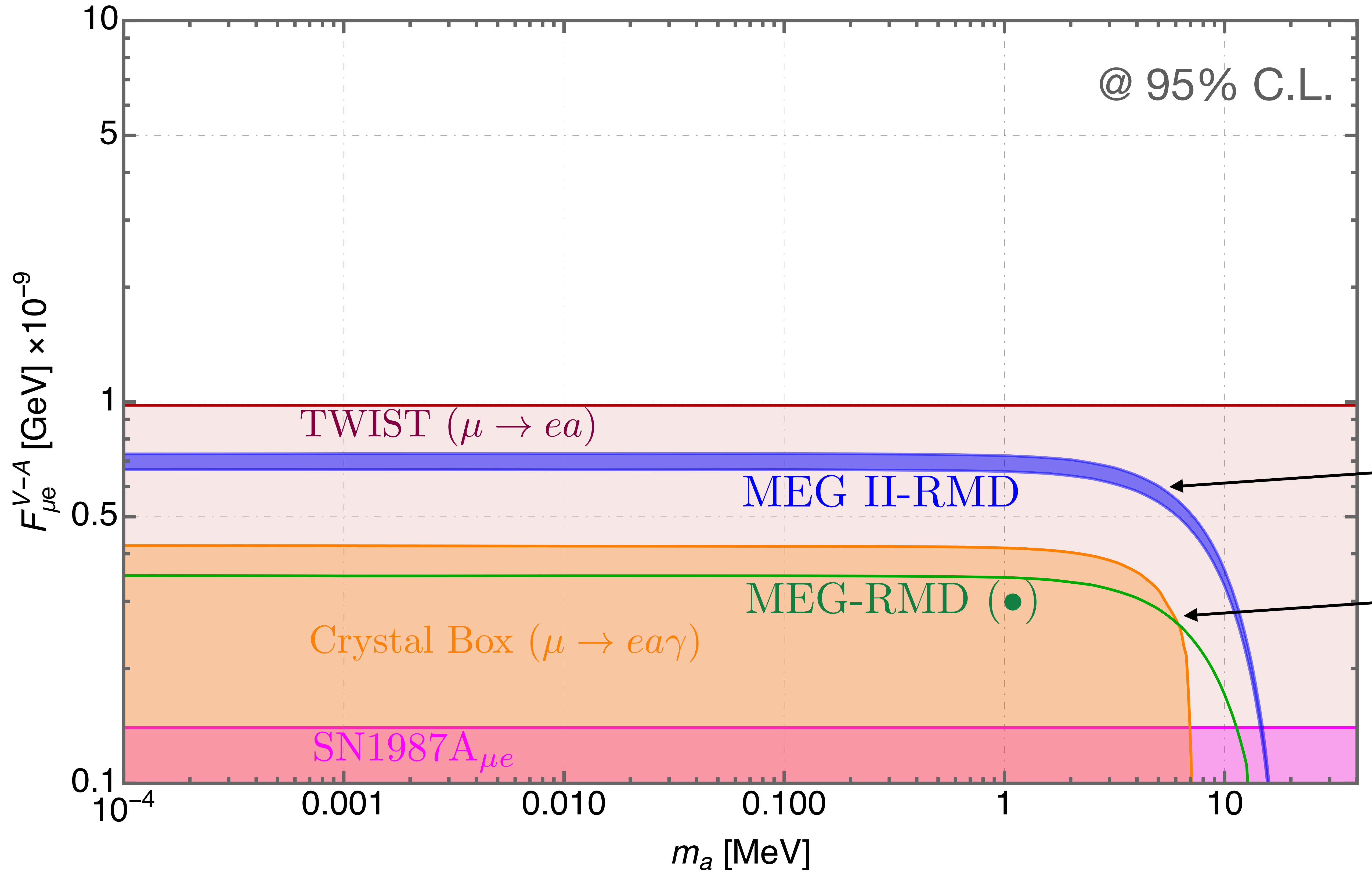
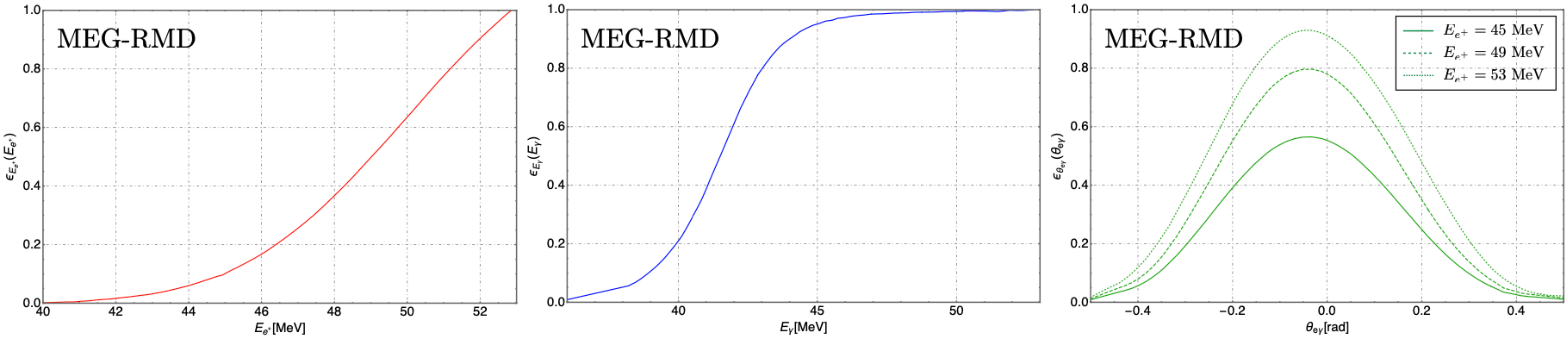


MEG II projection of the same analysis is still weaker than TWIST

MEG RMD data expected sensitivity is already comparable to Crystal Box!

Towards a new data taking strategy

Logic: the trigger requirements are killing the ALP signal



*

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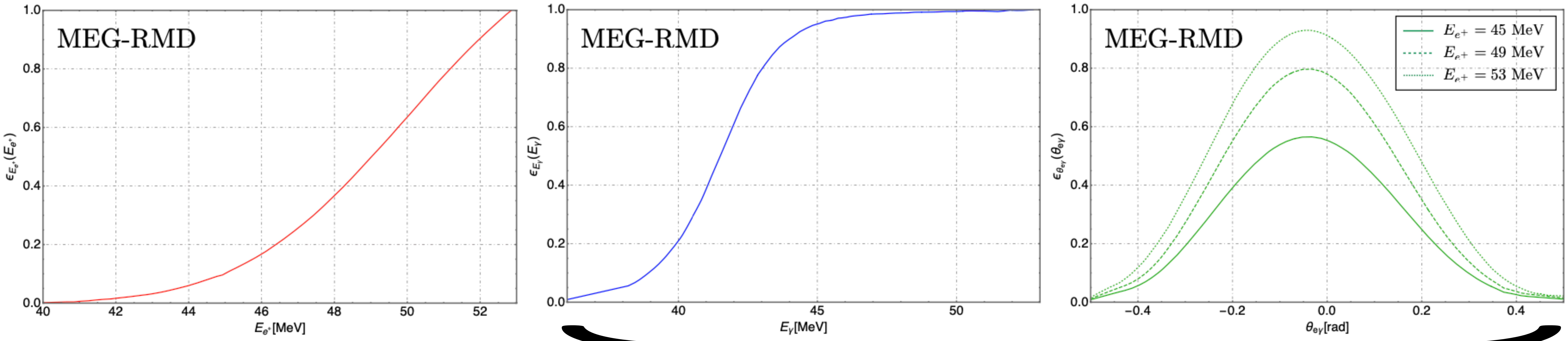

1) Eliminating the matching of the TC hit which assumes back to back topology

2) Lowering the photon trigger threshold reducing the beam intensity

*

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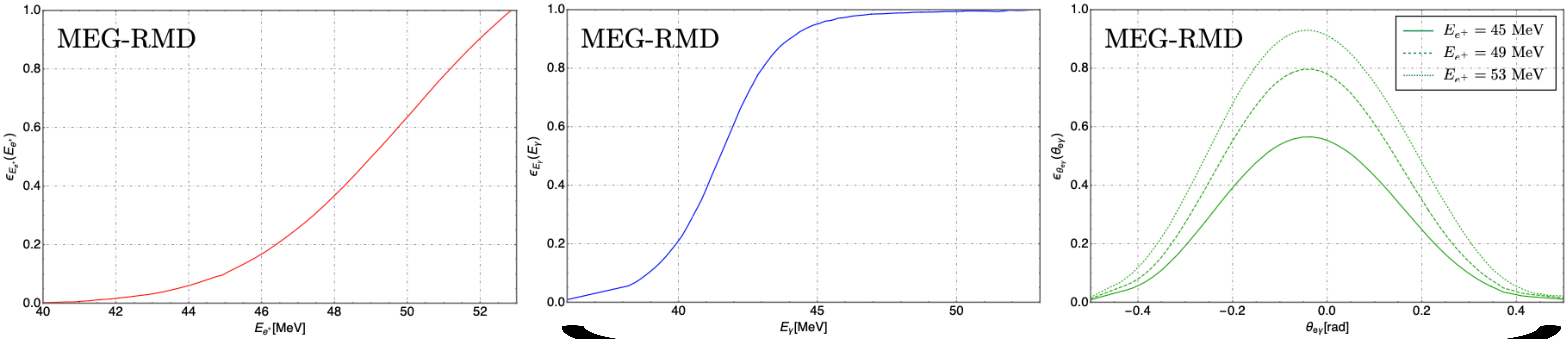

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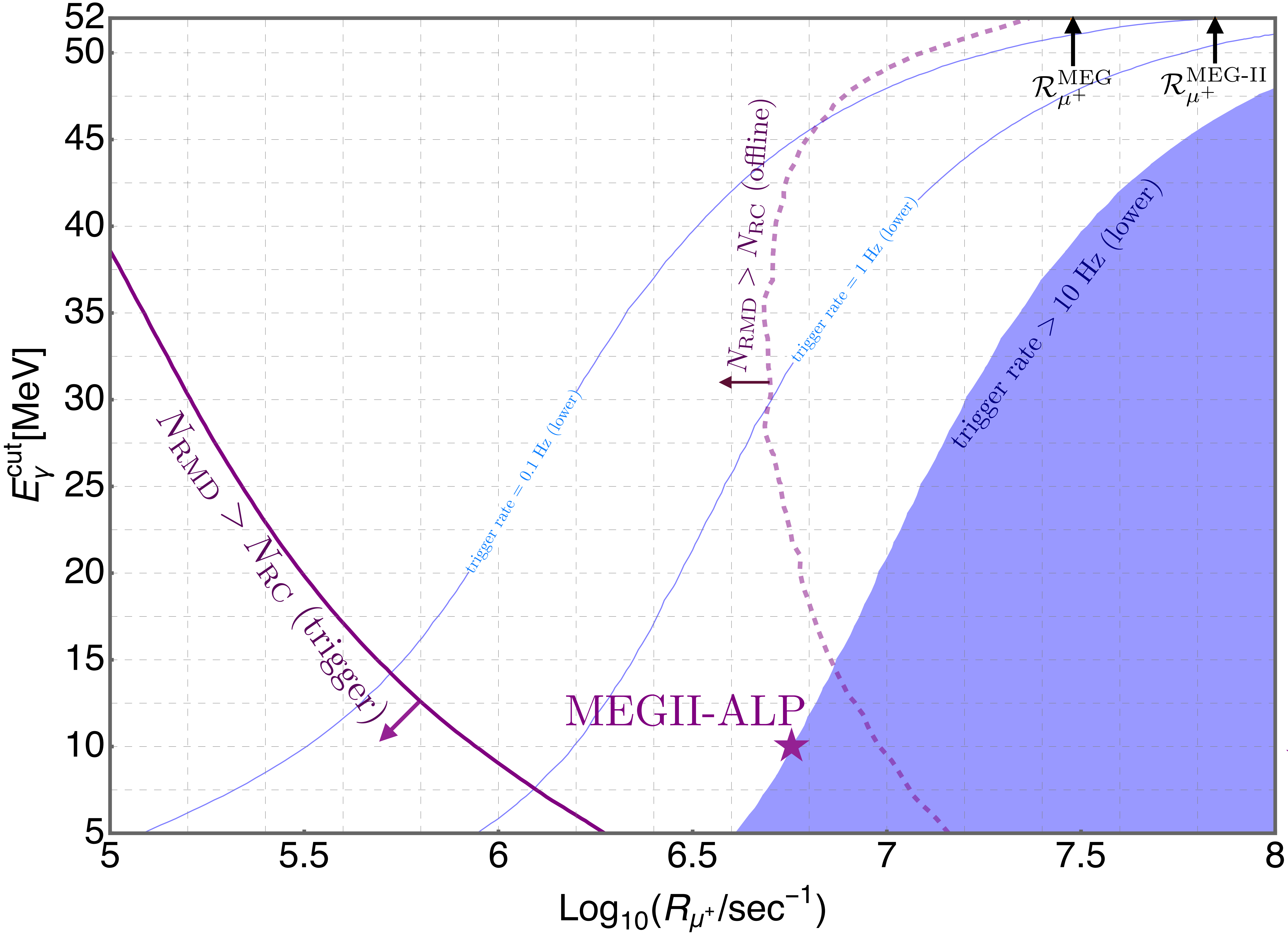
2) Lowering the photon trigger threshold reducing the beam intensity

The RC dominates the trigger rate but it can be suppressed by reducing the intensity R_μ*

$$\mathrm{RC} \sim R_\mu^2 \quad \mathrm{RMD} \sim R_\mu$$

*many thanks to Luca for teaching us all this!

Towards a new data taking strategy



Max trigger rate 10 Hz

fixes the intensity vs photon cut

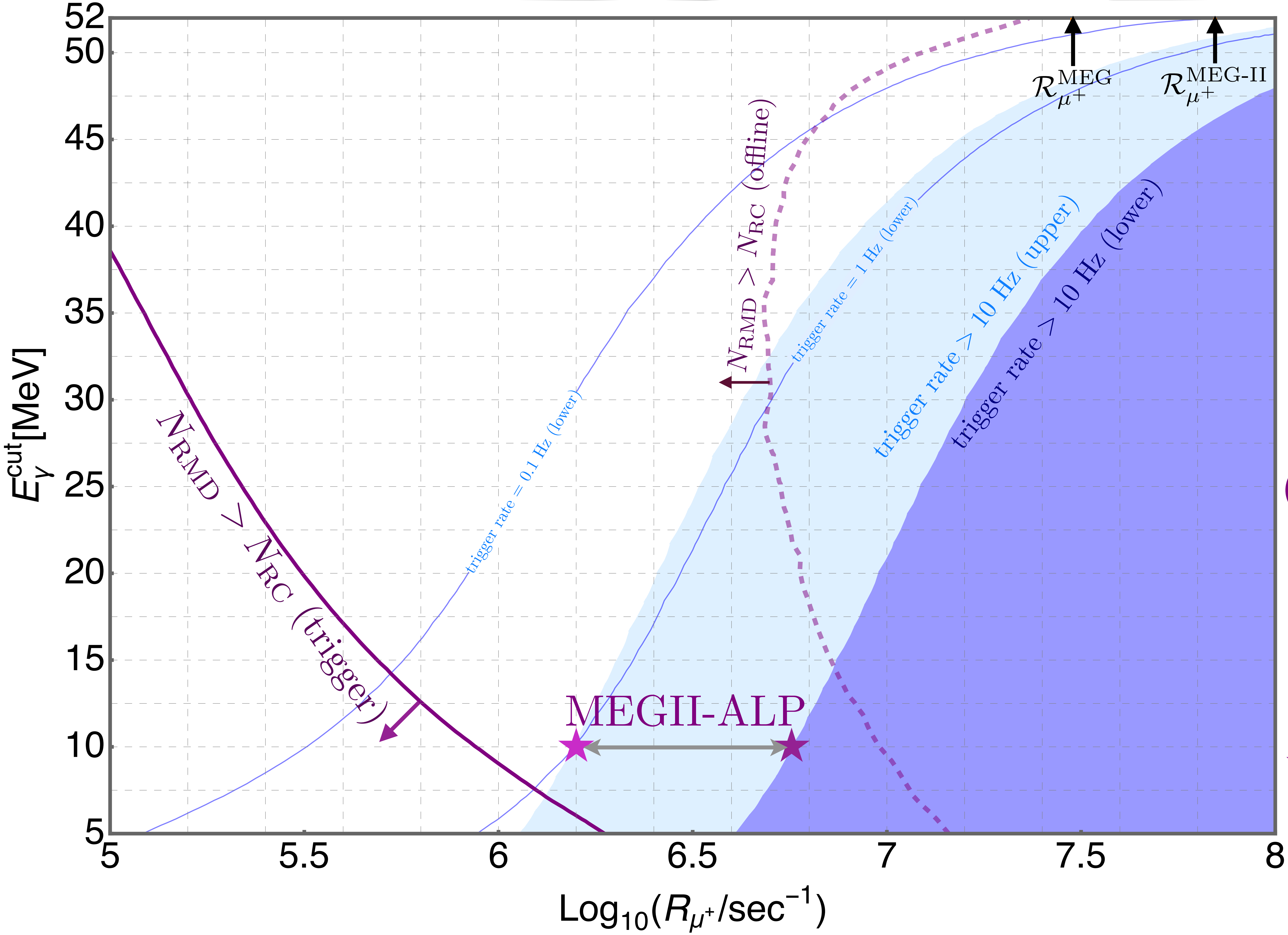
RMD becomes the dominant bed

below a certain intensity

(harder to suppress RMD online)

★ Benchmark fixed to the highest intensity for photon energy of 10 MeV given our estimate of the trigger rate

Towards a new data taking strategy II



Max trigger rate 10 Hz

fixes the intensity vs photon cut

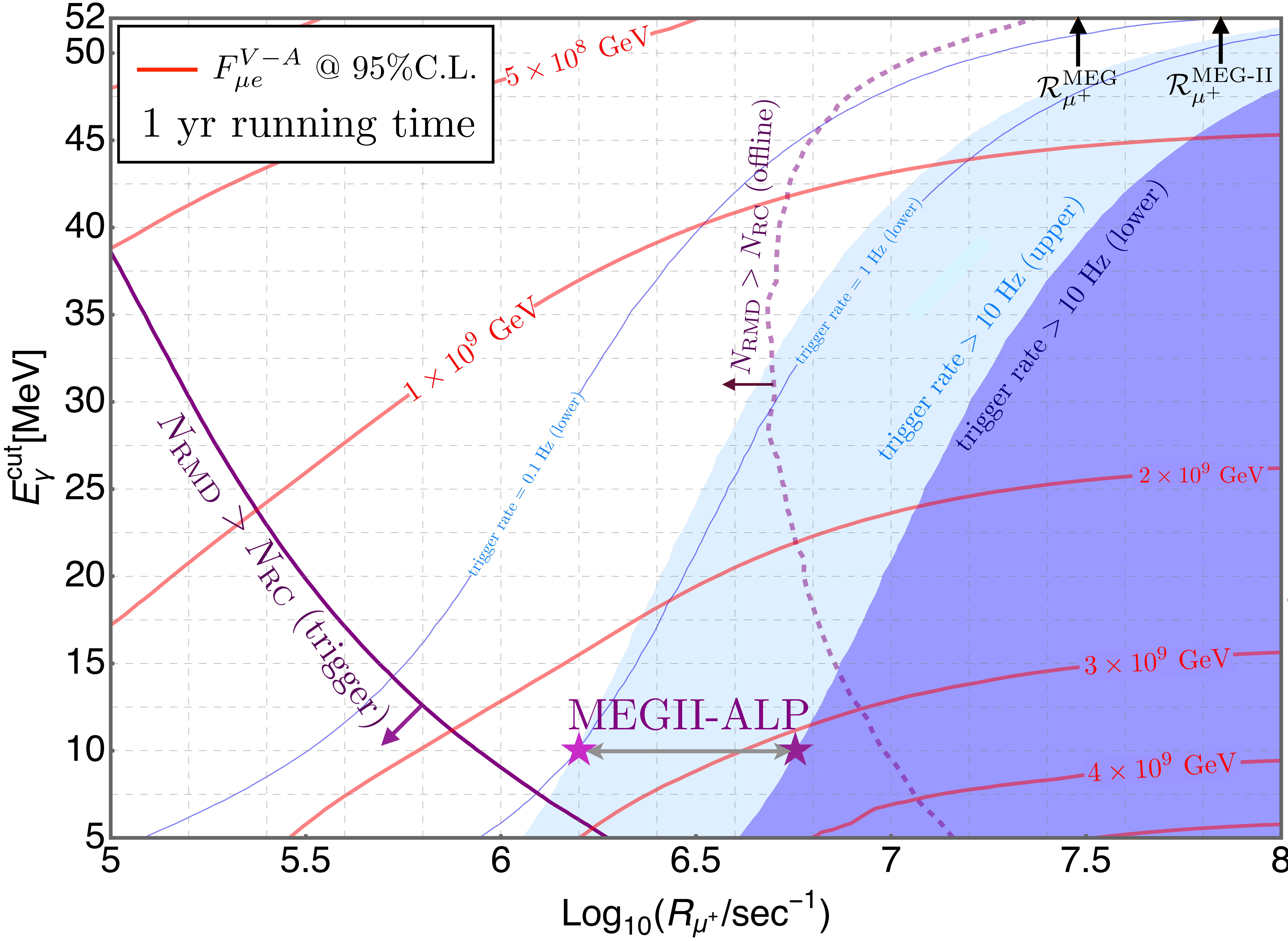
RMD becomes the dominant bkd

below a certain intensity

(harder to suppress RMD online)

★Uncertainty in trigger rate results in two different benchmark for the same photon energy

Towards a new data taking strategy III



Max trigger rate 10 Hz

fixes the intensity vs photon cut

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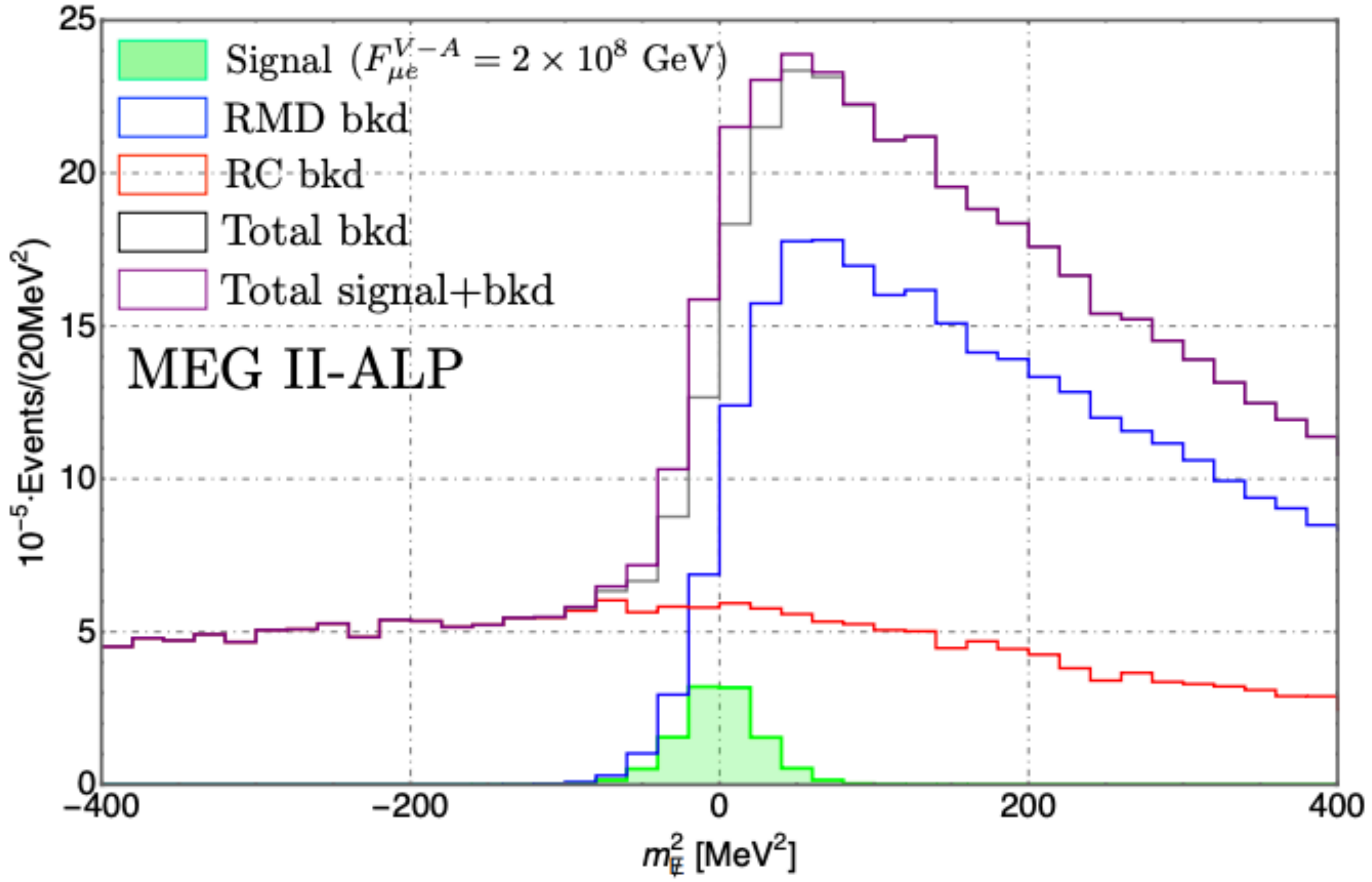
below a certain intensity

(harder to suppress RMD online)

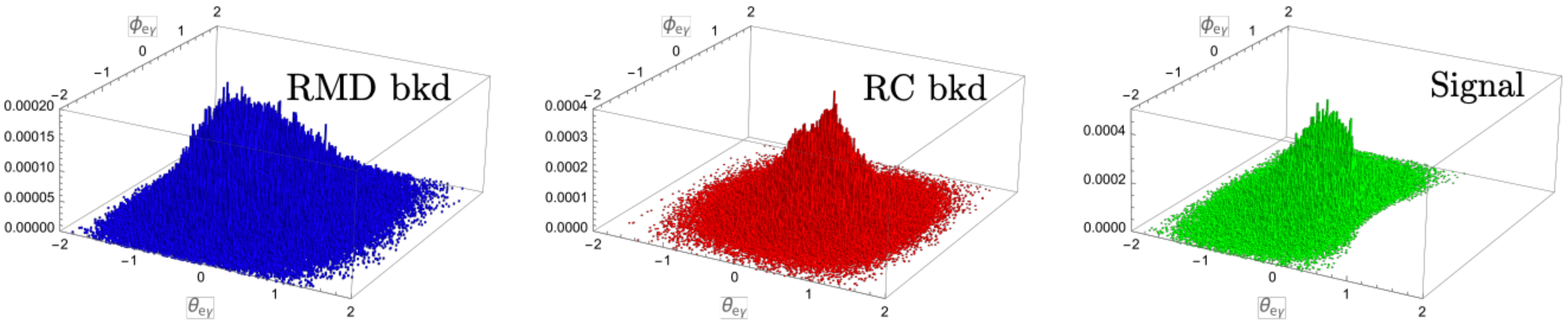
The reach is extracted at each point!

Final reach



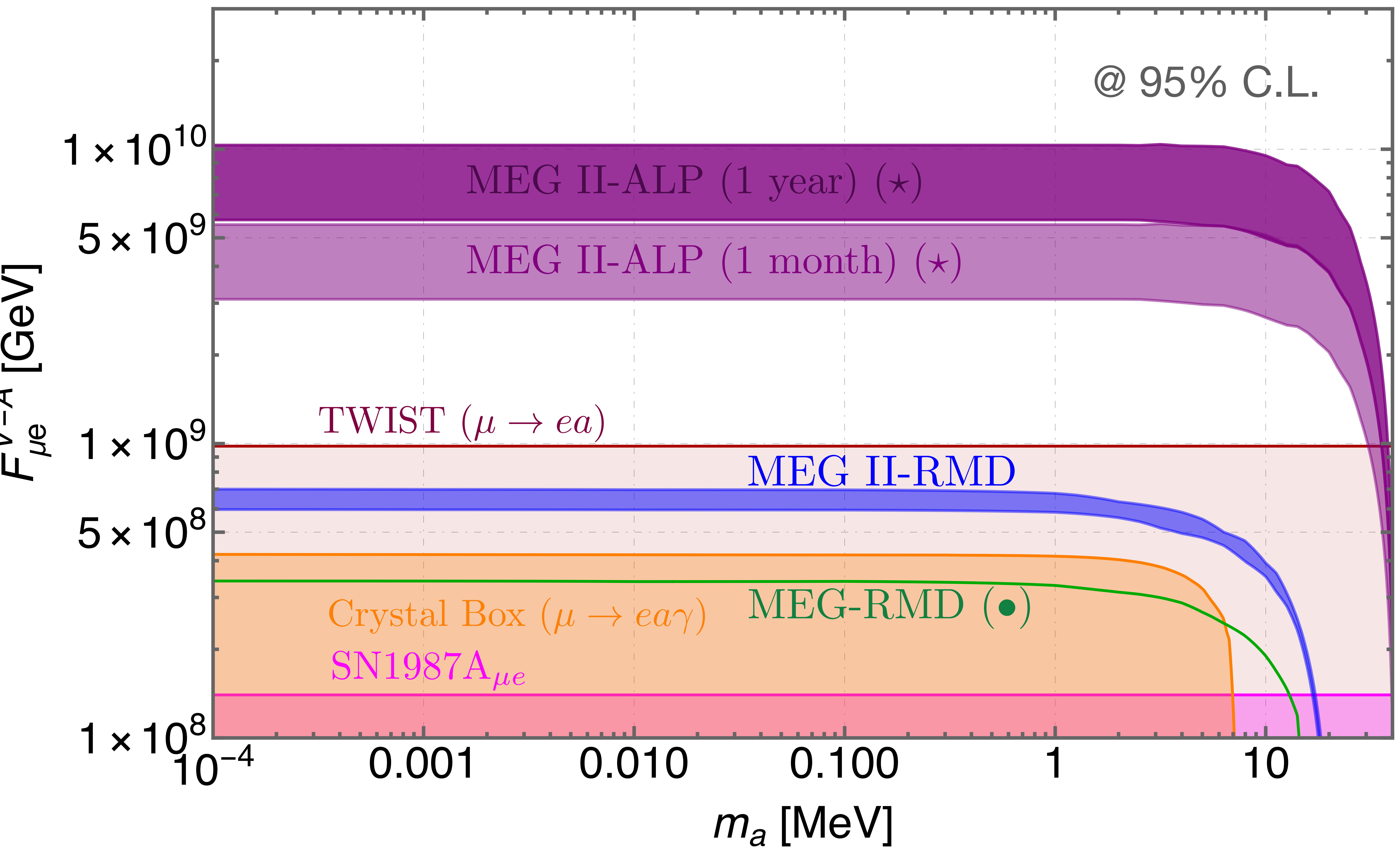
Bump hunt in missing mass*

*for a massless object we are close to a cliff of the bkd (systematics has to be taken into account)



Log-likelihood on angular variables

What can we test?



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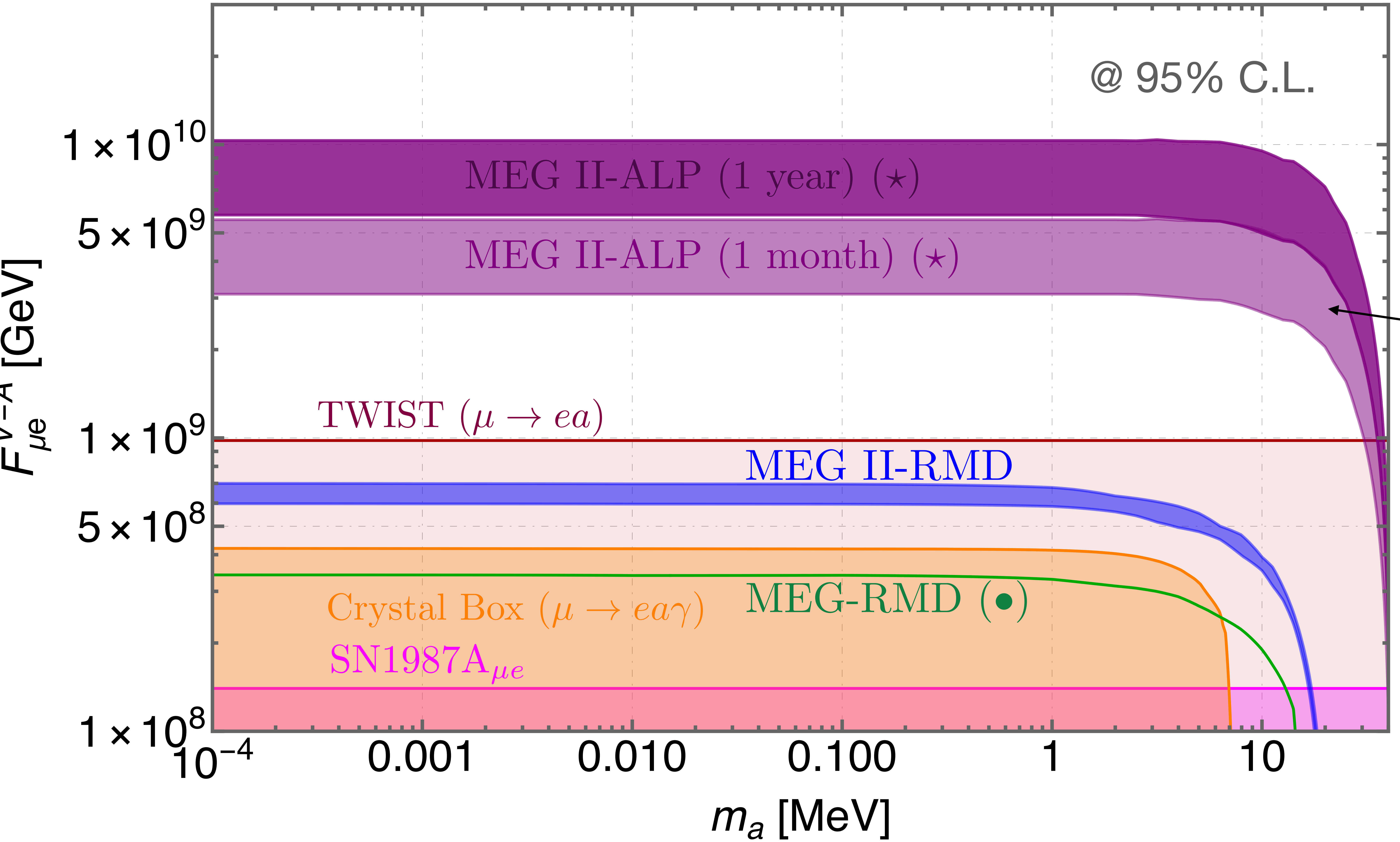

MEG II-ALP can improve on TWIST with only 1 month of data taking*

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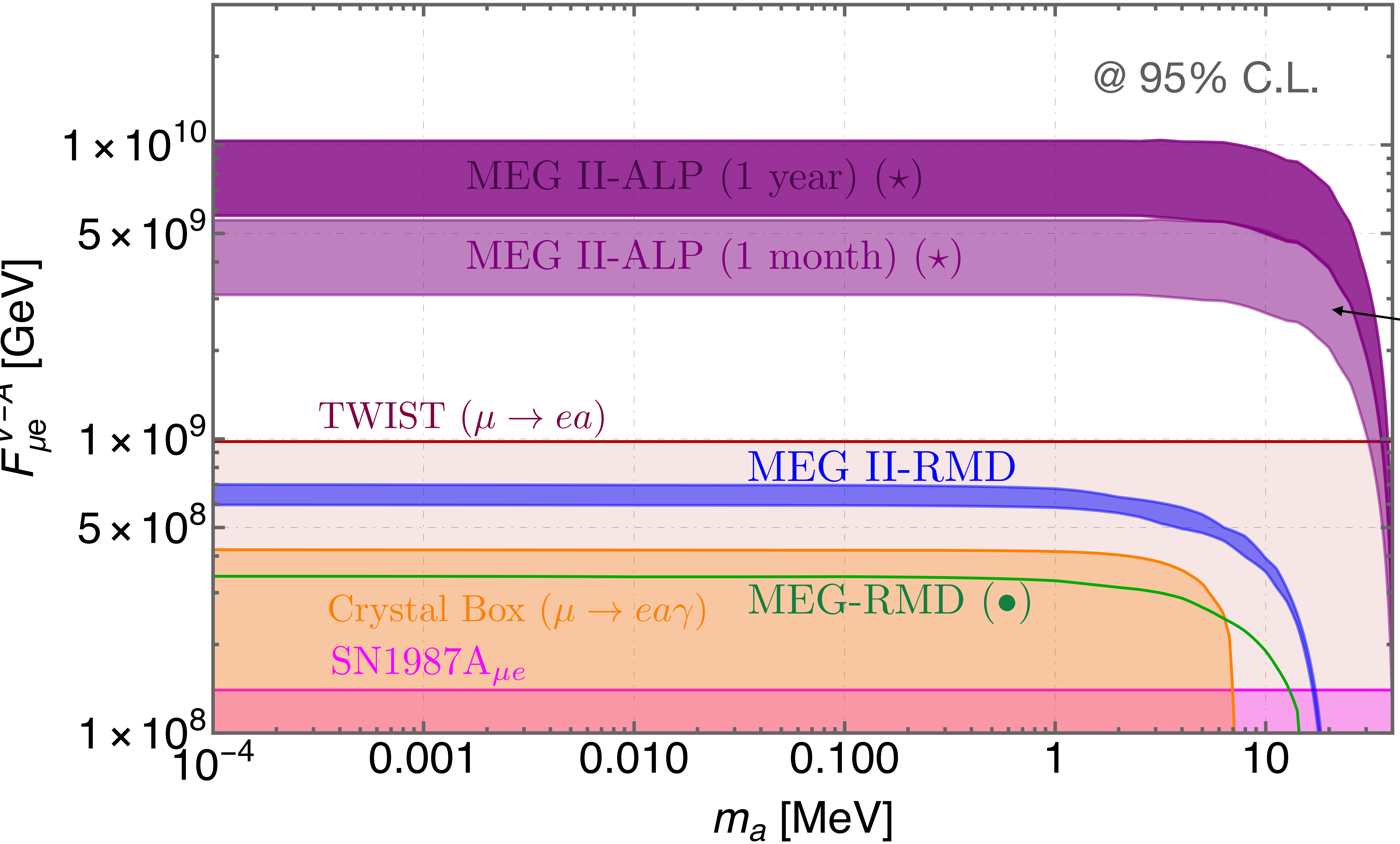

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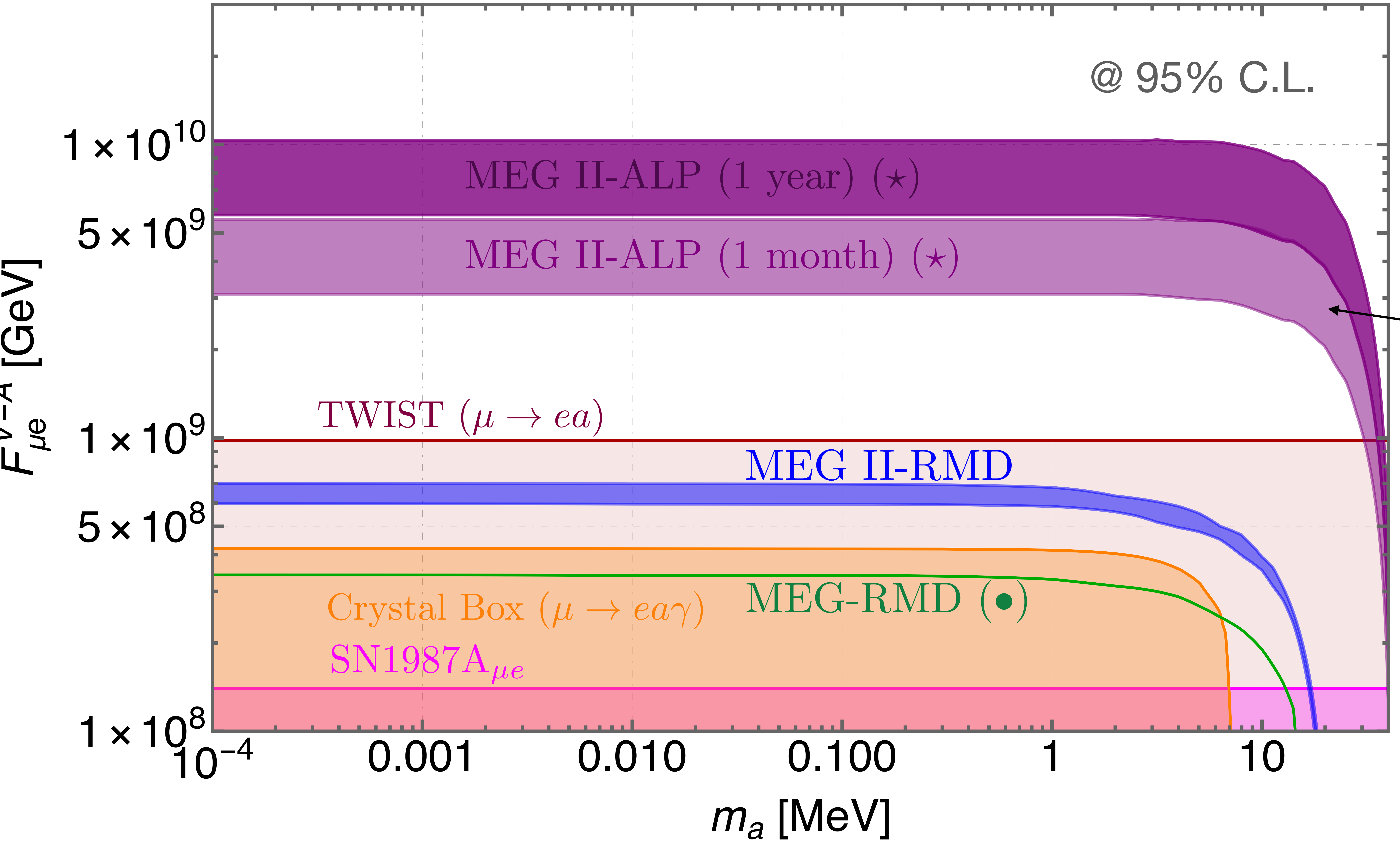

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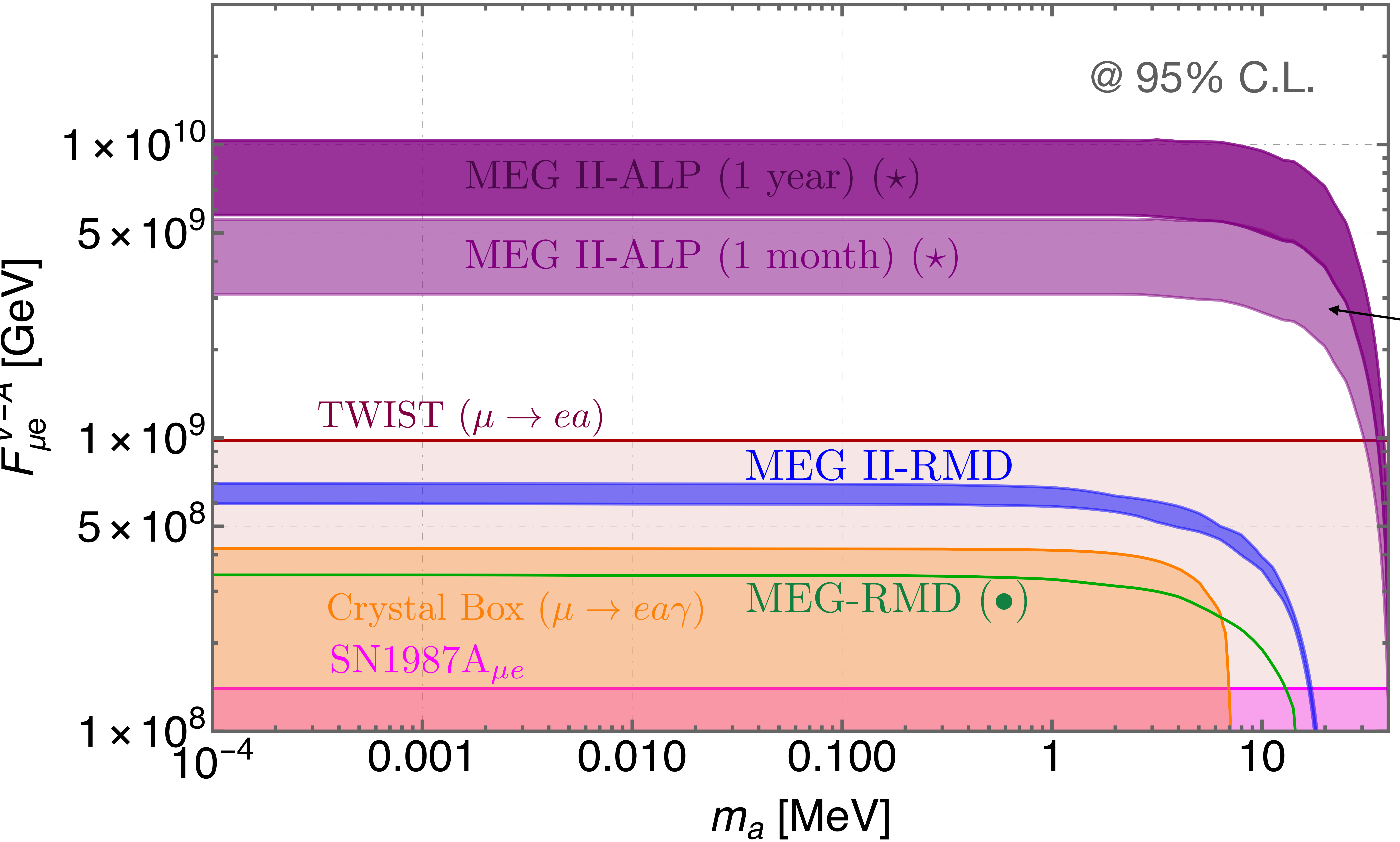

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Preliminary results of the MEG-II collaboration show that our estimate on the trigger performances has been conservative!

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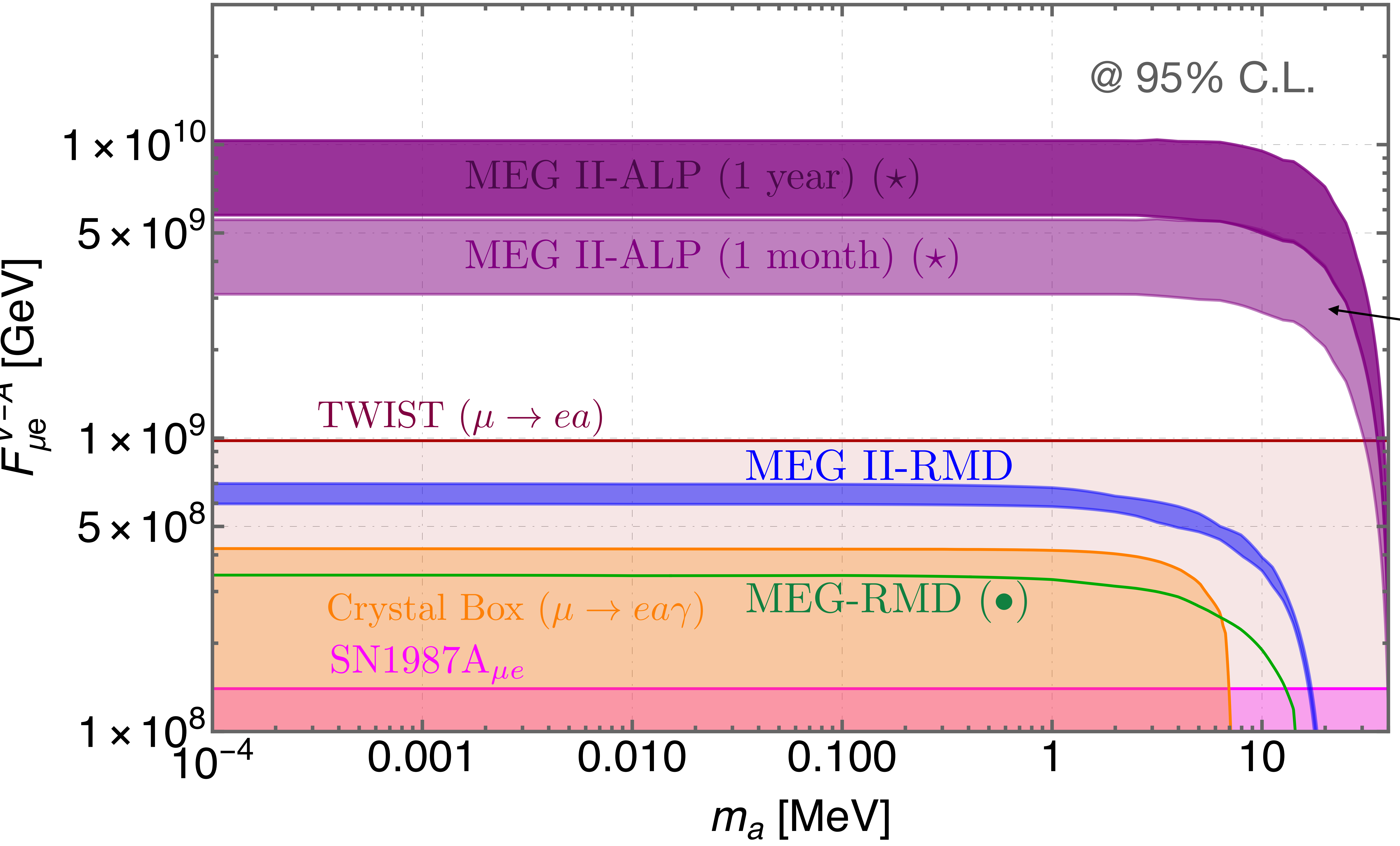

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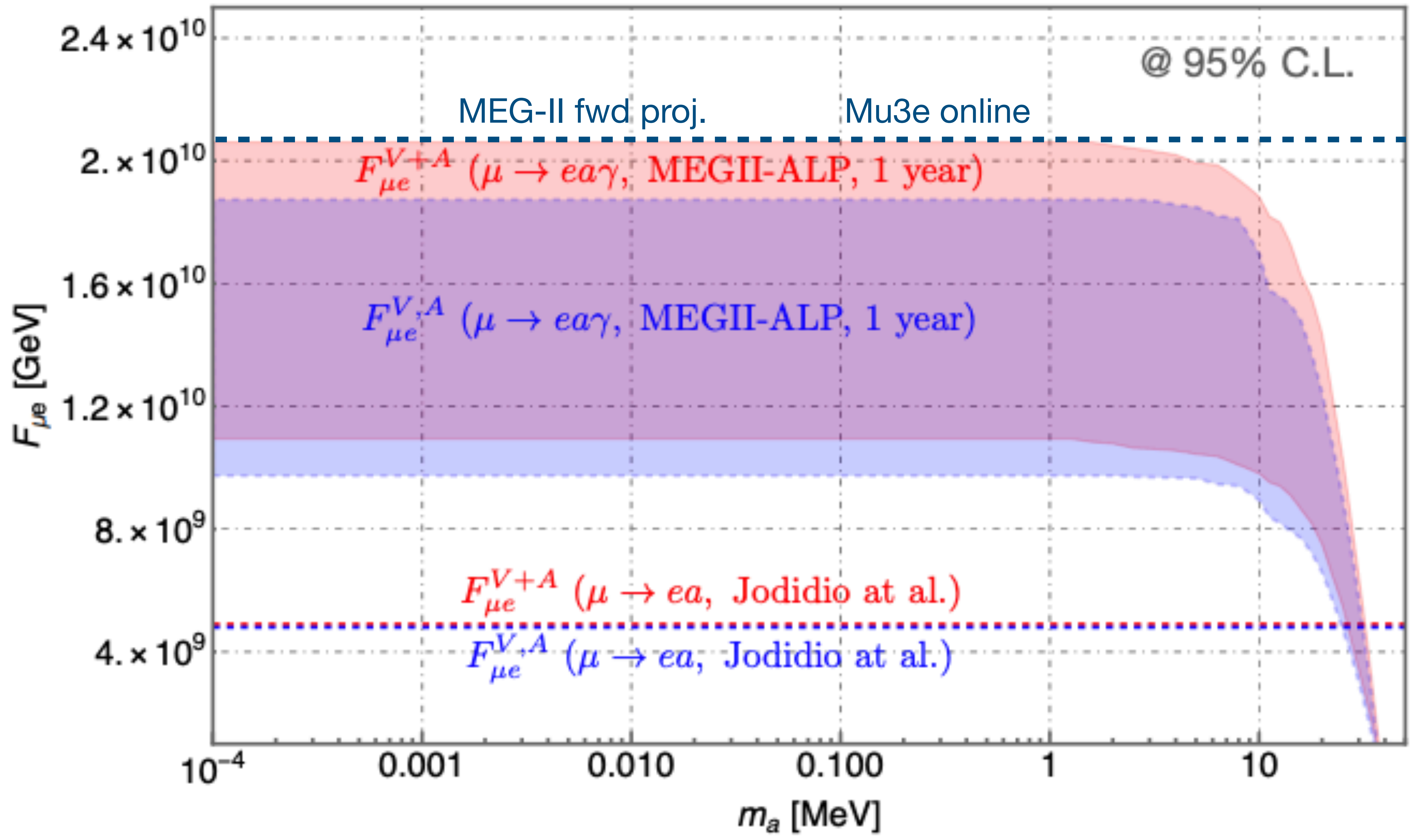
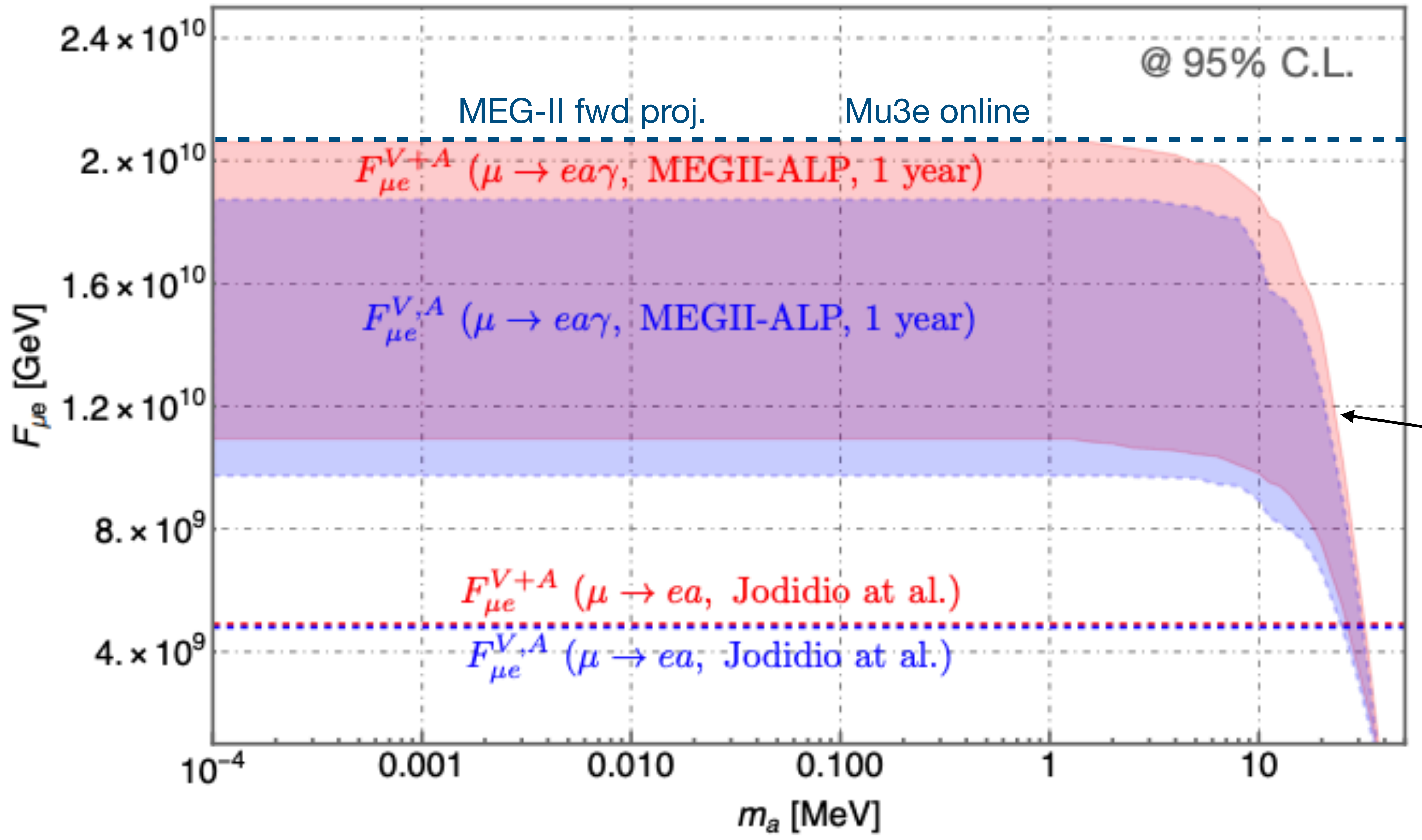
(Luca Galli for more infos)

Different ALP chiral structures



MEG-II ALP is the best way to explore ~ a decade of unconstrained parameter space ~ NOW

Different ALP chiral structures



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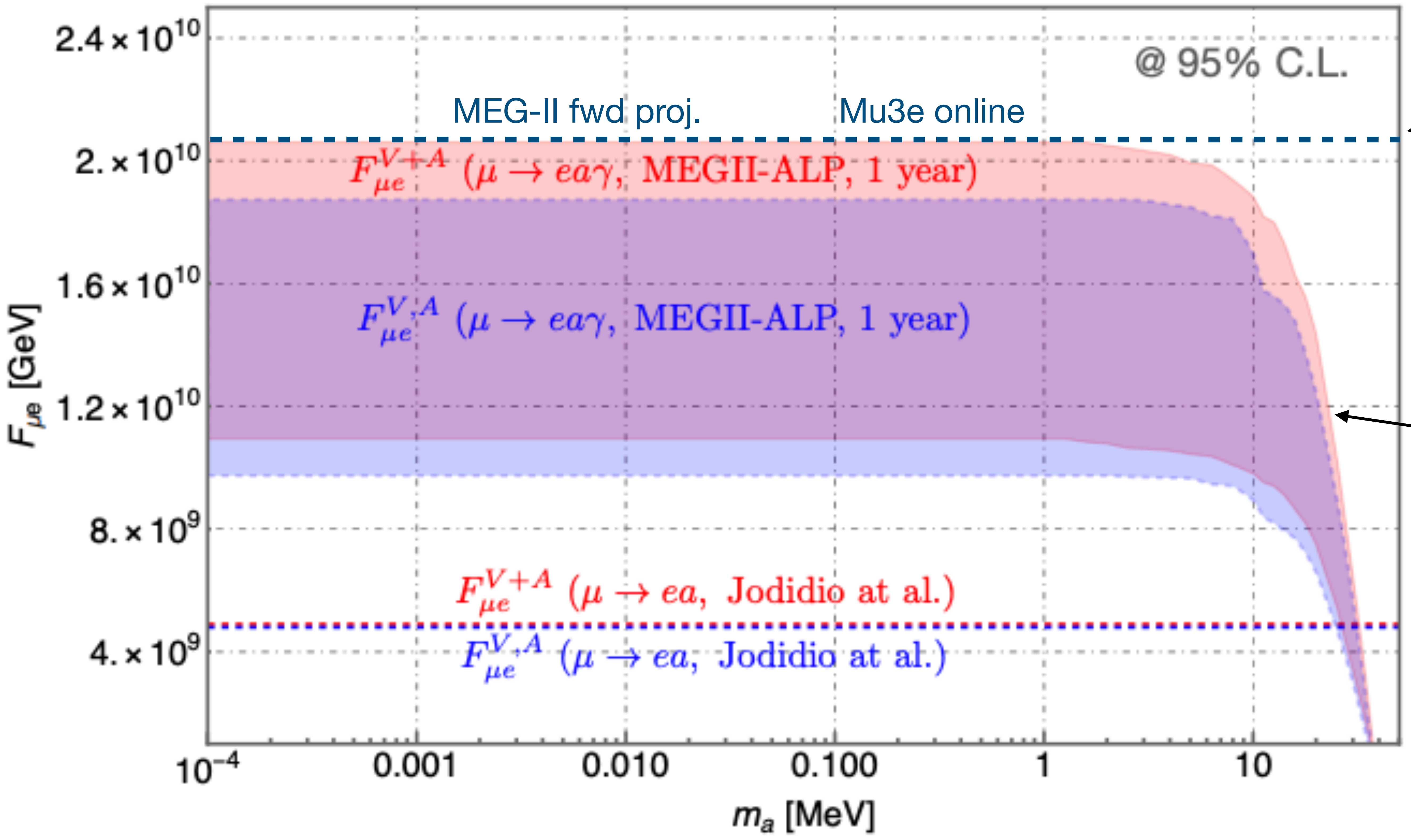


Mu3e online. Perrevoort 2018

A dedicated fwd experiment
under optimal experimental conditions
F=100, % level precision, 10^14 muons

MEG II-ALP can improve
on TWIST with only
1 month of data taking*

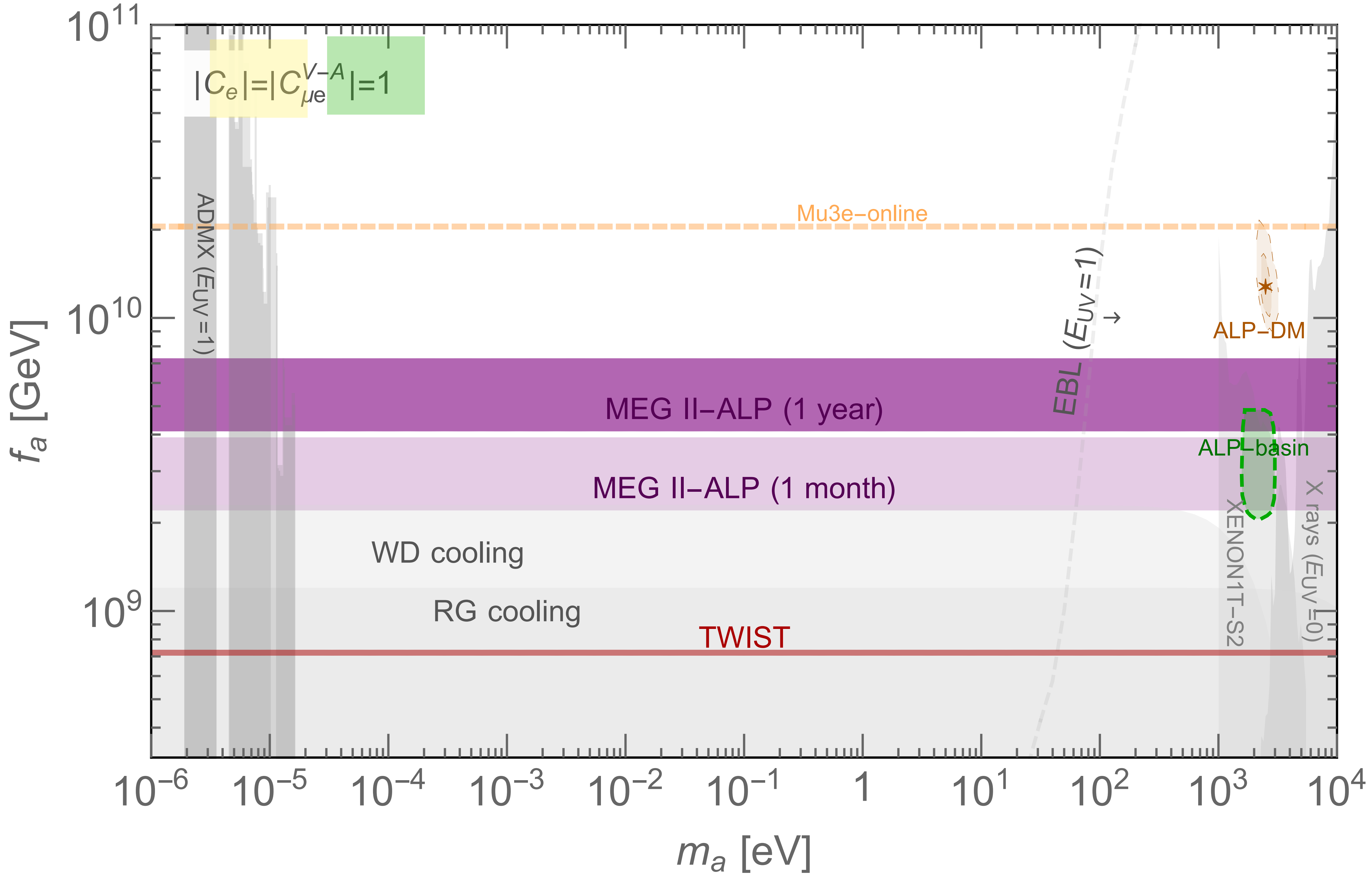
MEG-II ALP is the best way to explore ~ a decade of unconstrained parameter space ~ NOW

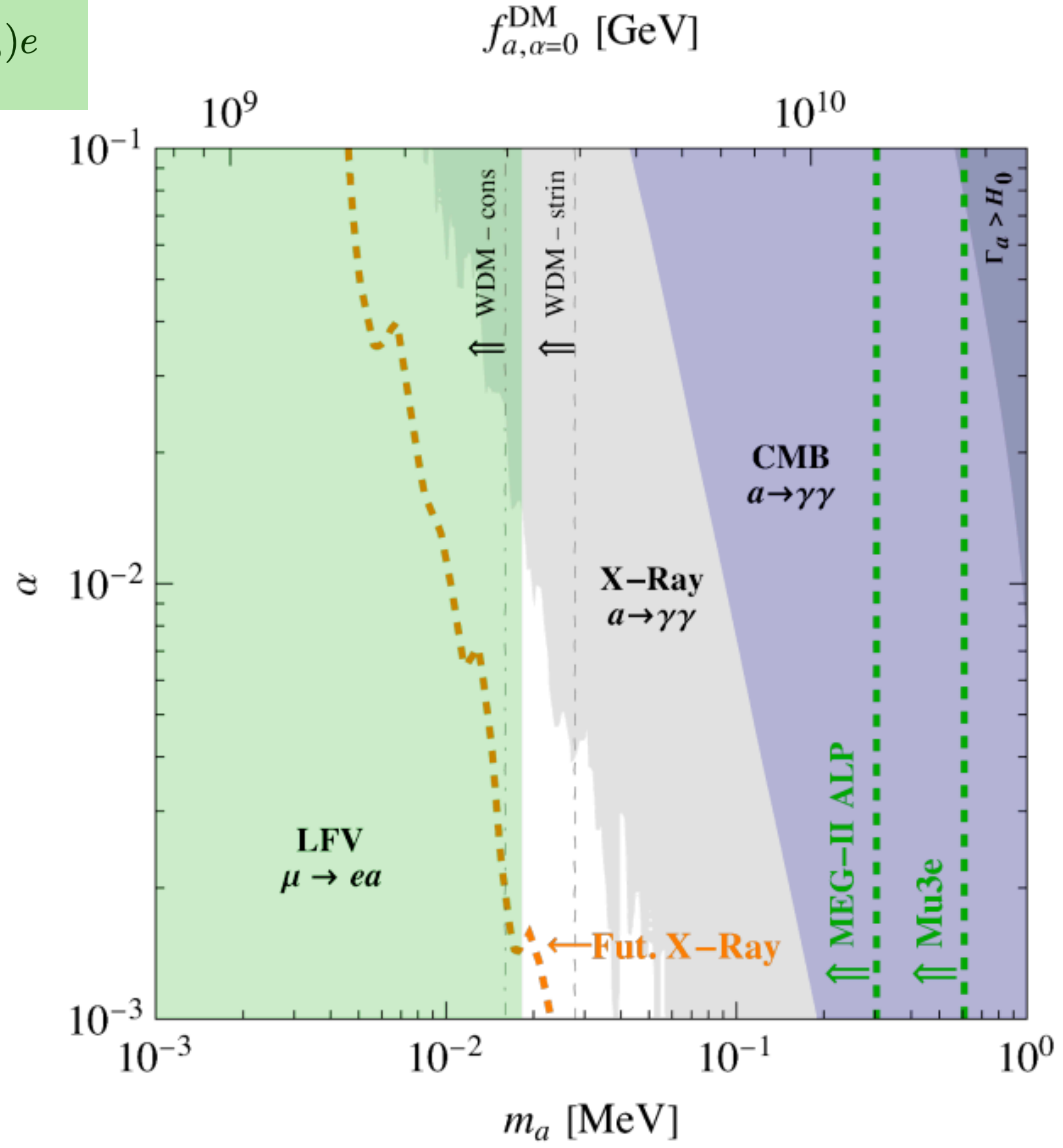
Back to theory land

axions coupled to leptons anarchically: *flavor diagonal* = *flavor off-diagonal*

$$\frac{\partial_\mu a}{f_a}\bar{e}\gamma^\mu\gamma_5 e \quad = \quad \frac{\partial_\mu a}{2f_a}\bar{\mu}\gamma^\mu(C^V_{\mu e}+C^A_{\mu e}\gamma_5)e$$

Panci, Redigolo, Schwetz Ziegler 2209.03371





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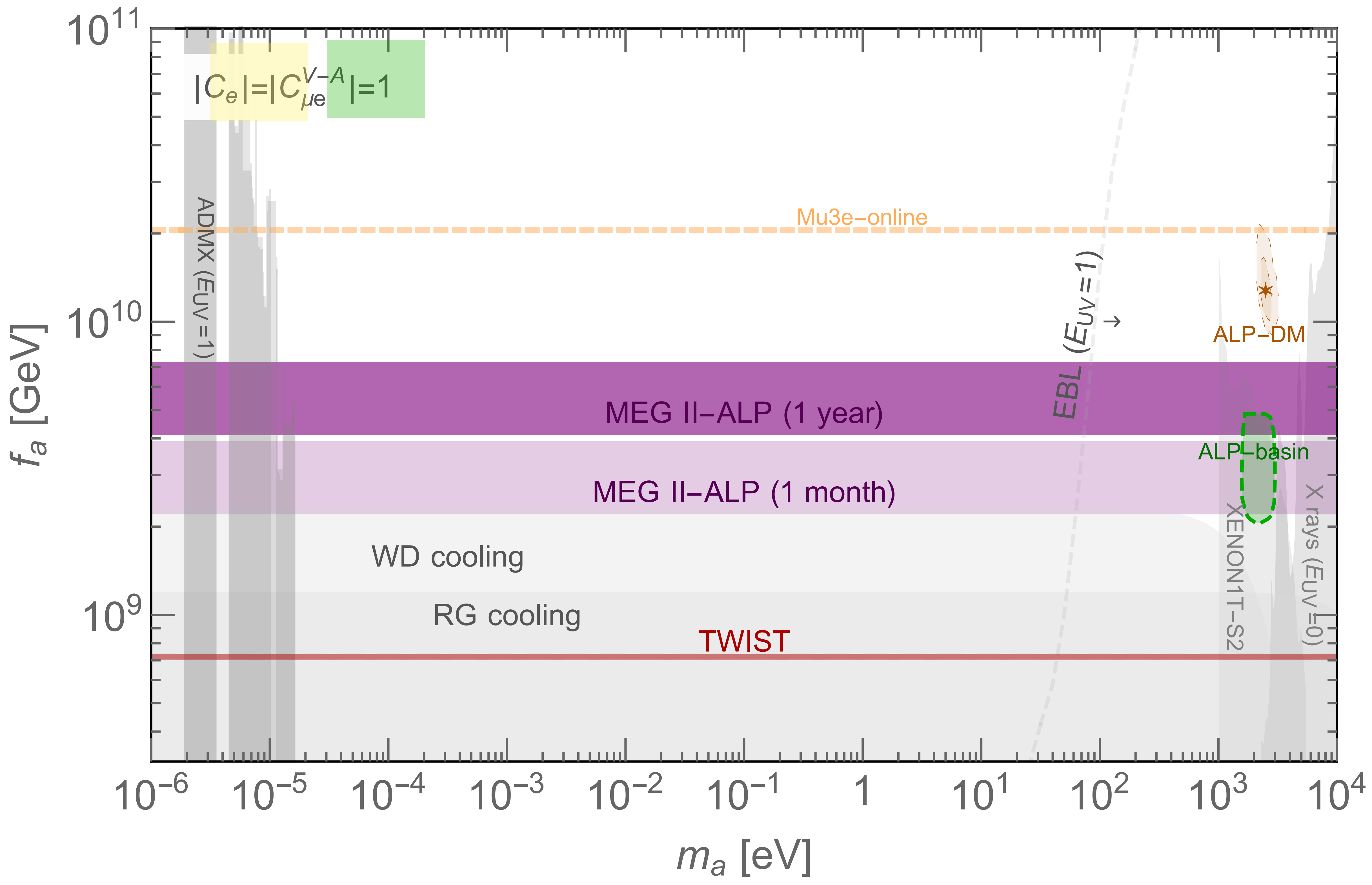

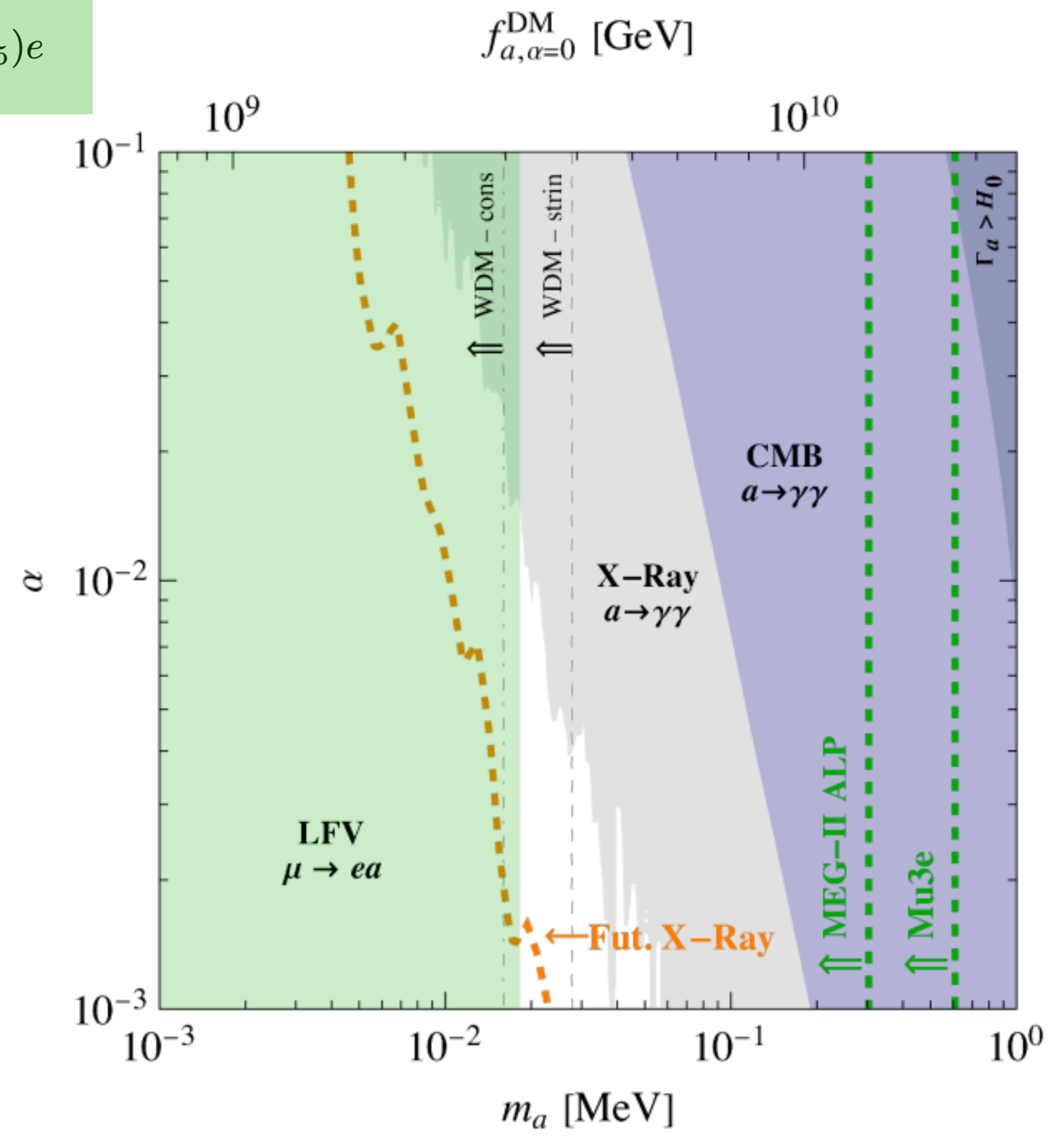

MEG-II can surpass bounds from star cooling!

Back to theory land

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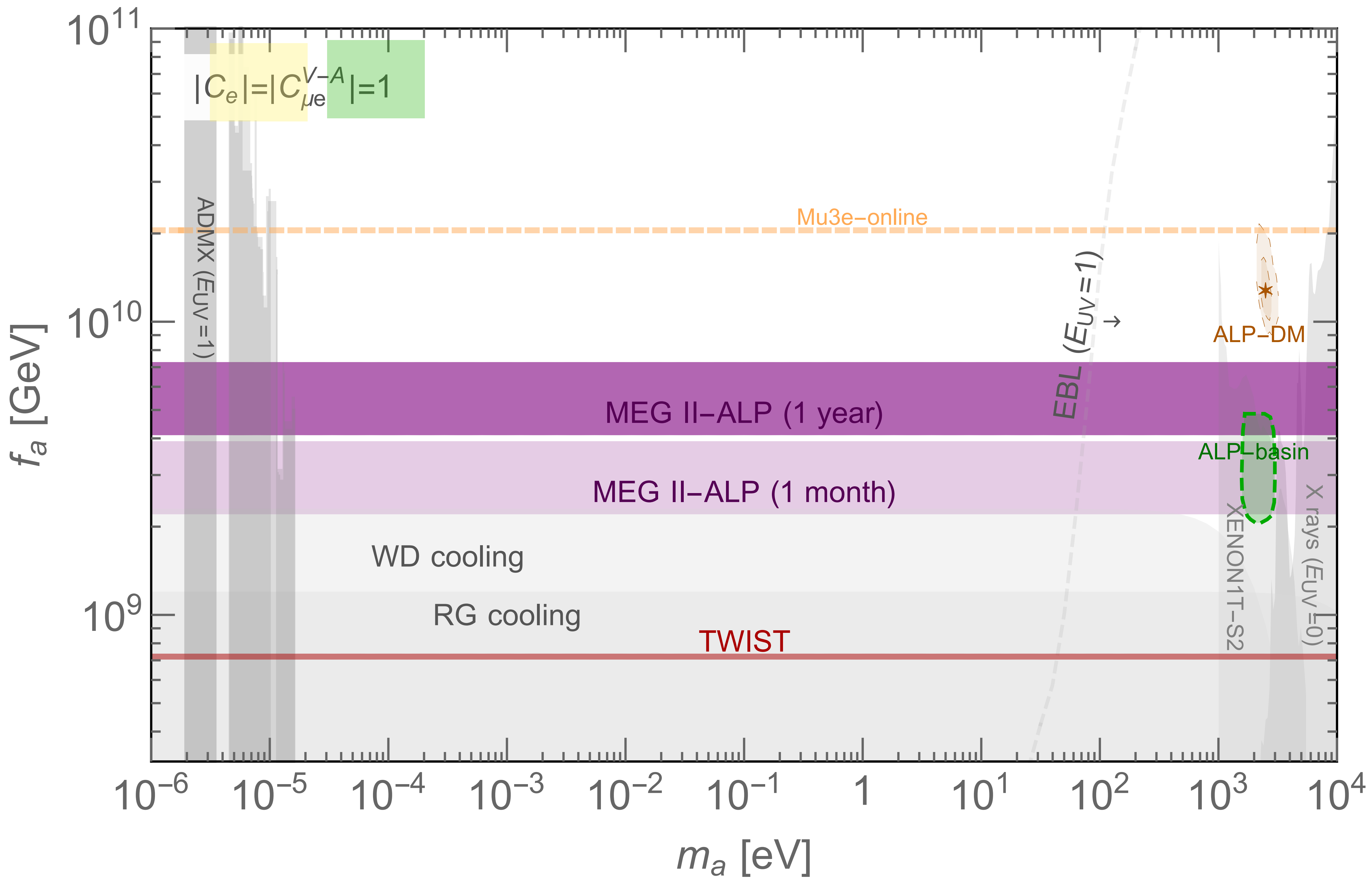
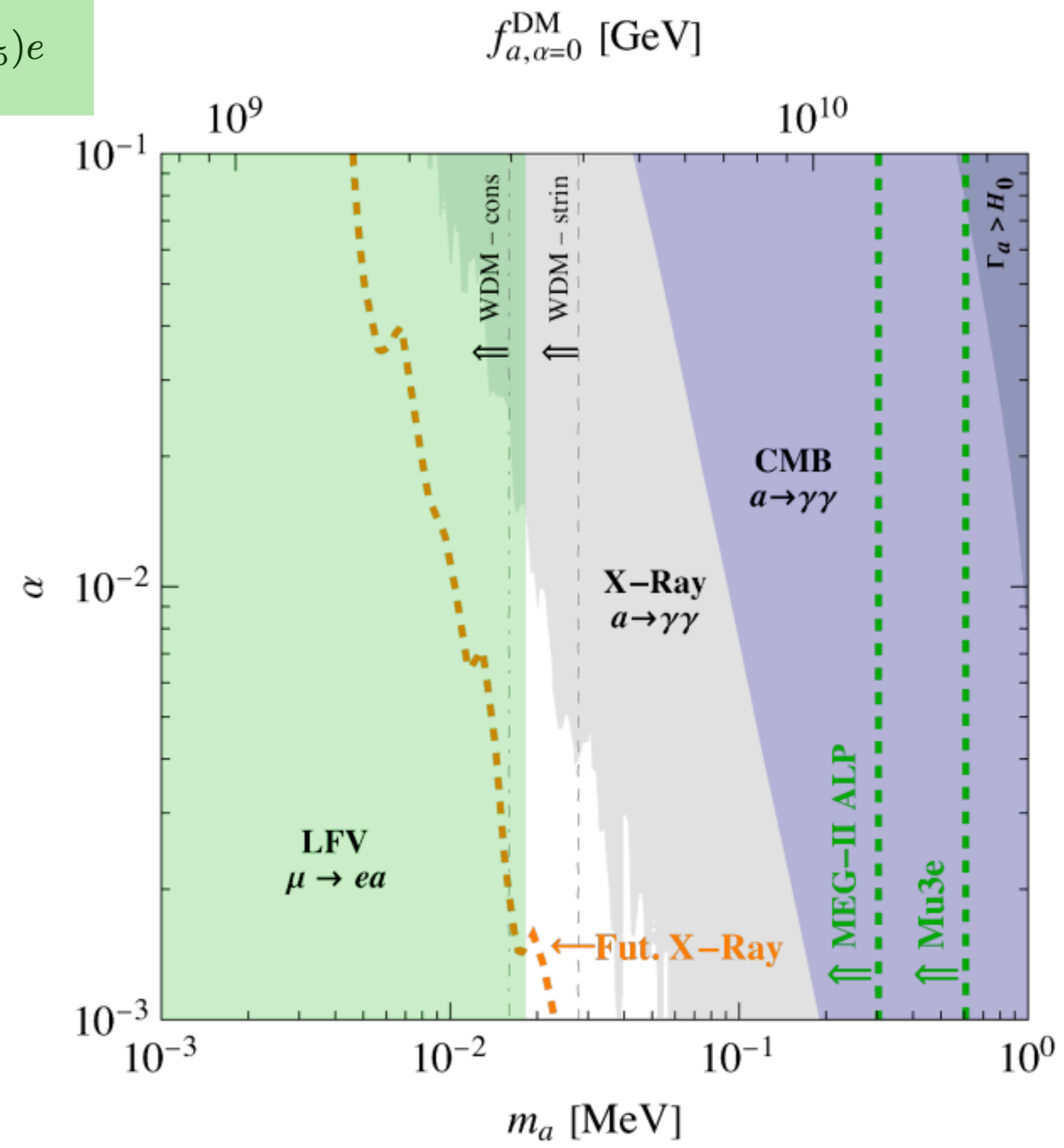




MEG-II can surpass bounds from star cooling!

MEG-II can completely test Freeze-in model based on LFV decays

Flavor preserving light new physics

The presence of light states can give final states close enough to FV muon decays without breaking any SM accidental symmetry!

Example: $\mathcal{L}_{\gamma'} \supset F'^{\mu\nu} F'_{\mu\nu} + m_A A'^{\mu} A'_{\mu} + \epsilon A'^{\mu} J_{\mu}^{\text{SM}}$

See. *Echenard, Essig and Zhong 1409.0638*

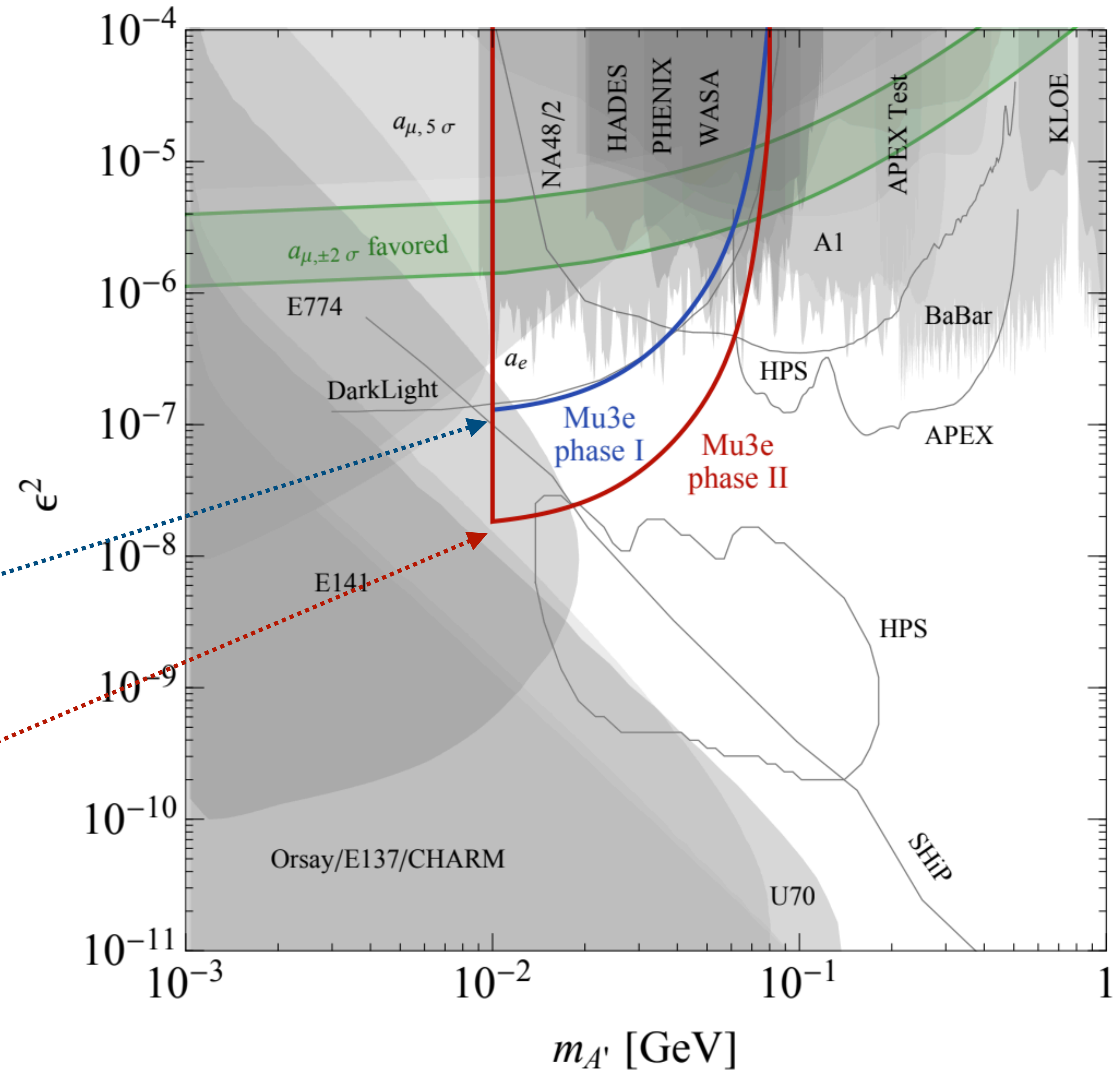
$$\mu^+ \to e^+ \nu \bar{\nu} \gamma' \to e^+ \nu \bar{\nu} (e^+ e^-)_{\text{res.}}$$

Bkd: $\mu \to e^+ \nu \bar{\nu} e^+ e^-$

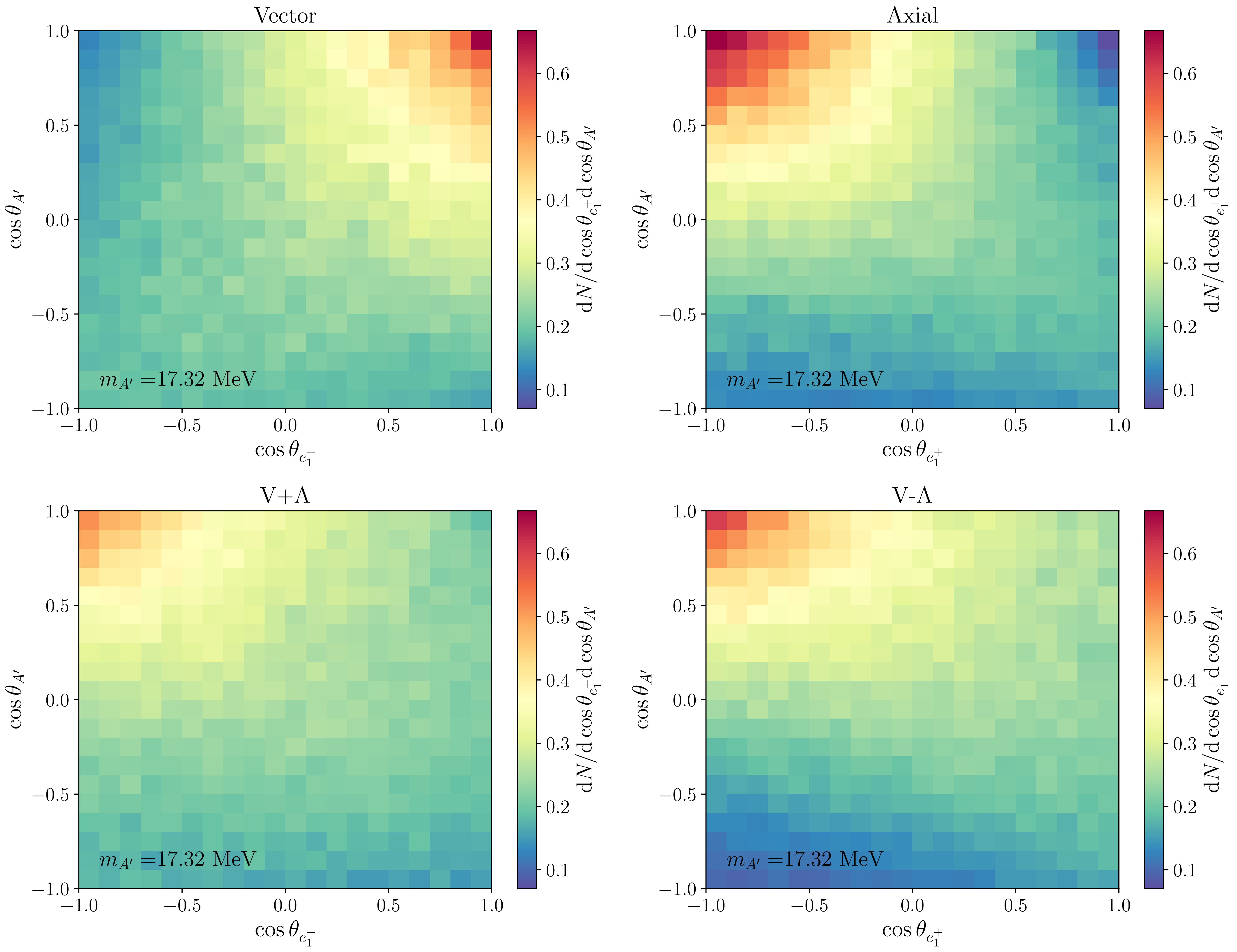
bump-hunt in invariant mass

$10^{15} \mu^+$

$5.5 \times 10^{16} \mu^+$



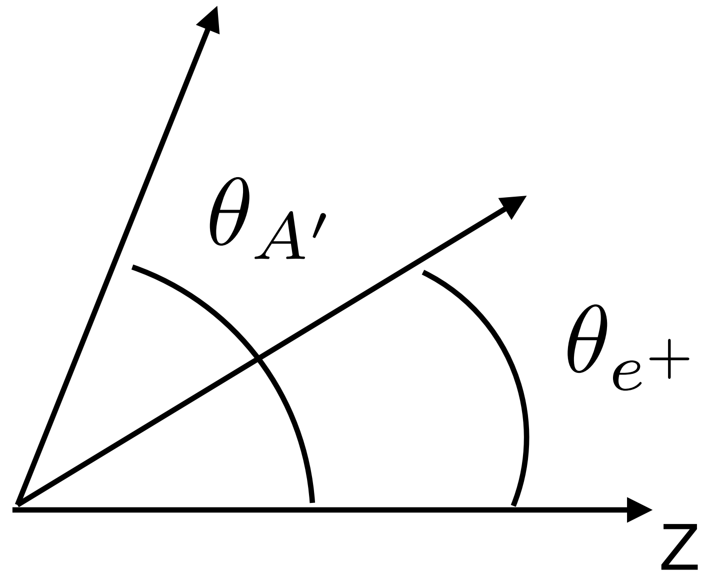
Distinguish vector chirality through angular distributions



PRELIMINARY

$$m_A A'^{\mu} A'_{\mu} + \epsilon A'^{\mu} J^{\mathrm{SM}}_{\mu}$$

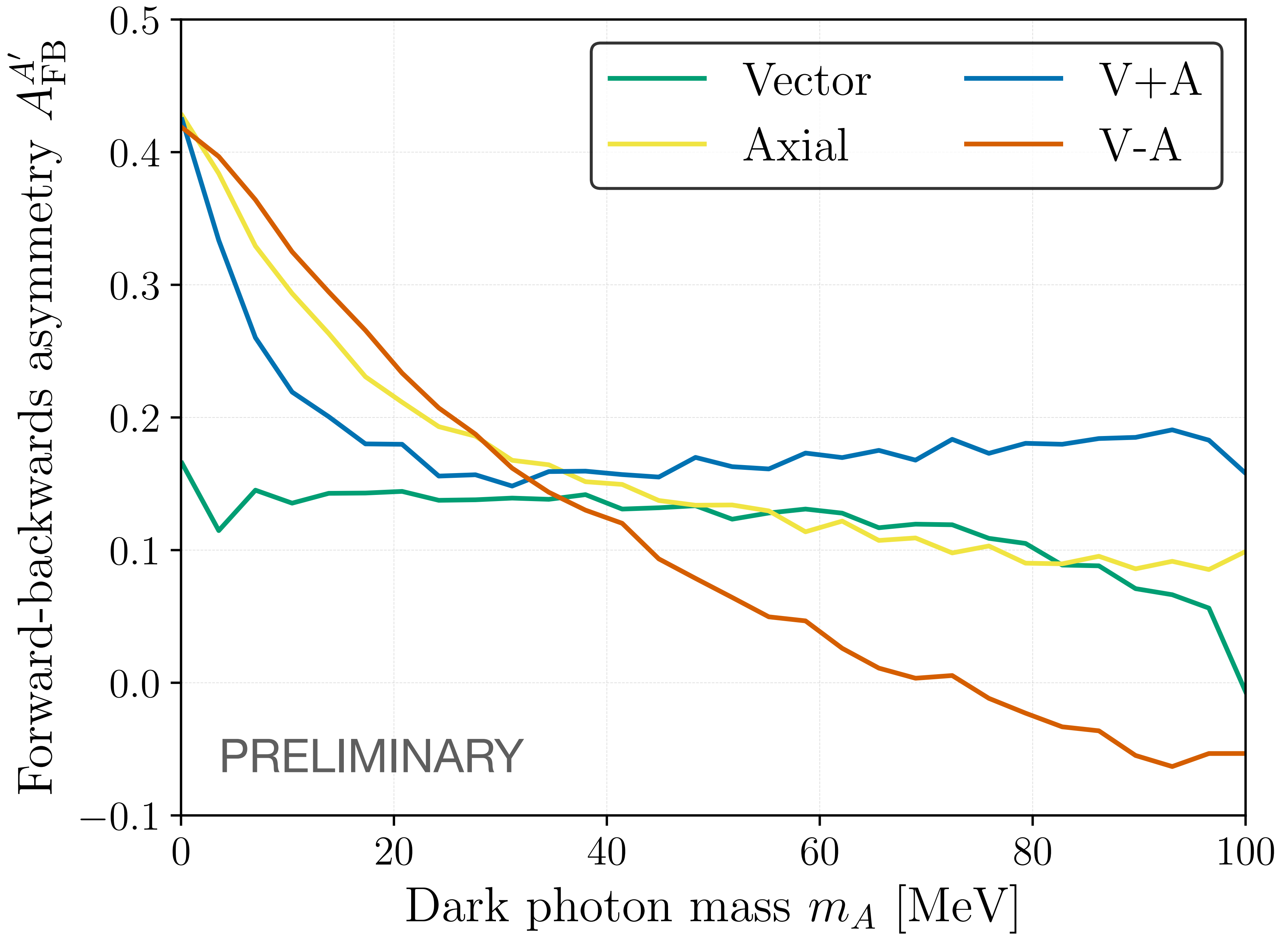
- Vector: $J^{\mathrm{SM}}_{\mu} = \bar{f}\gamma_{\mu} f$
- Axial: $J^{\mathrm{SM}}_{\mu} = \bar{f}\gamma_{\mu}\gamma_5 f$
- Right: $J^{\mathrm{SM}}_{\mu} = \bar{f}\gamma_{\mu}(1+\gamma_5) f$
- Left: $J^{\mathrm{SM}}_{\mu} = \bar{f}\gamma_{\mu}(1-\gamma_5) f$

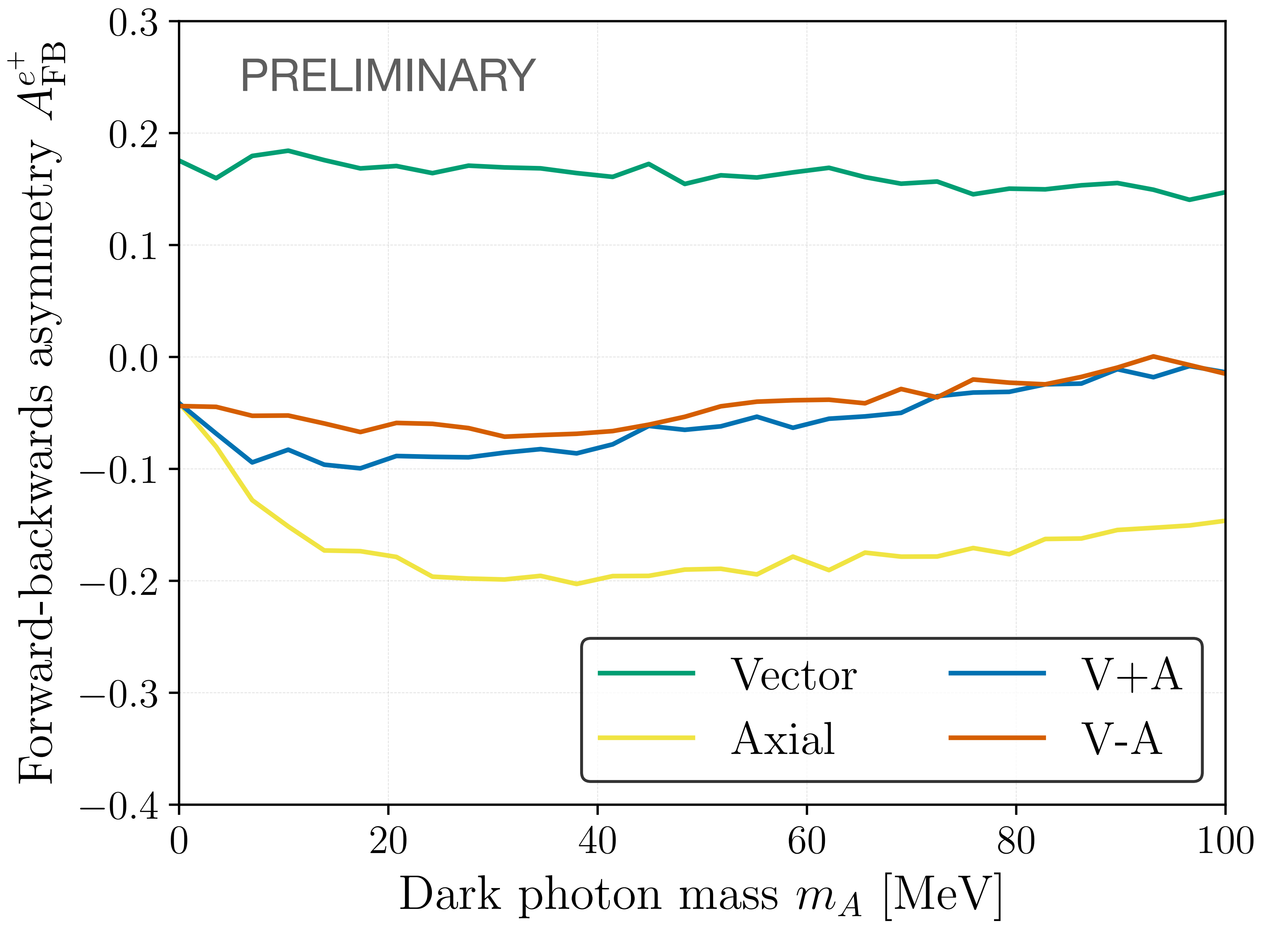


Angular cuts

to suppress background and to distinguish signals

$$A \equiv \frac{F - B}{F + B} \qquad F = \int d\cos\theta \frac{d\Gamma}{d\cos\theta} \qquad B = \int_{-1}^{0} d\cos\theta \frac{d\Gamma}{d\cos\theta}$$

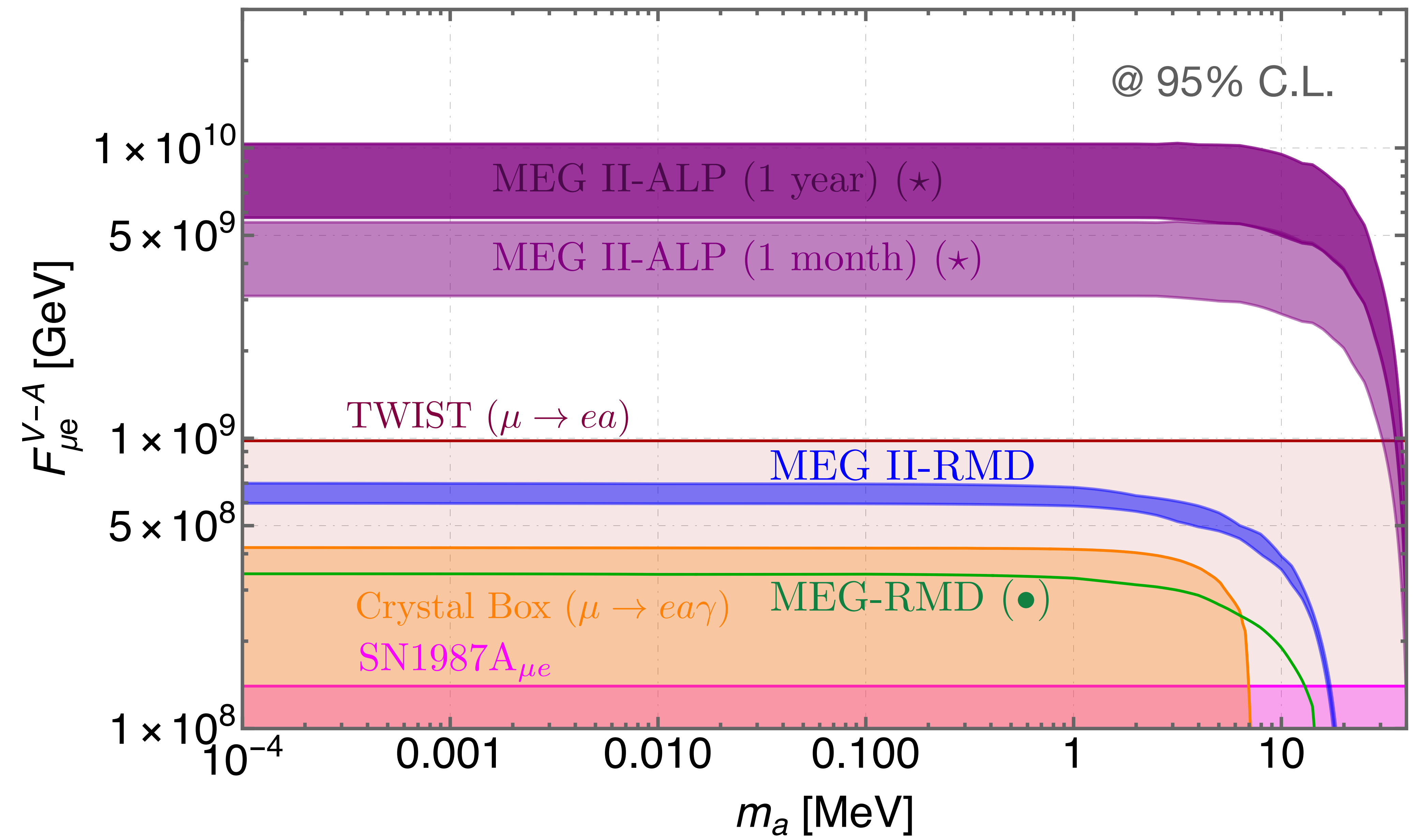




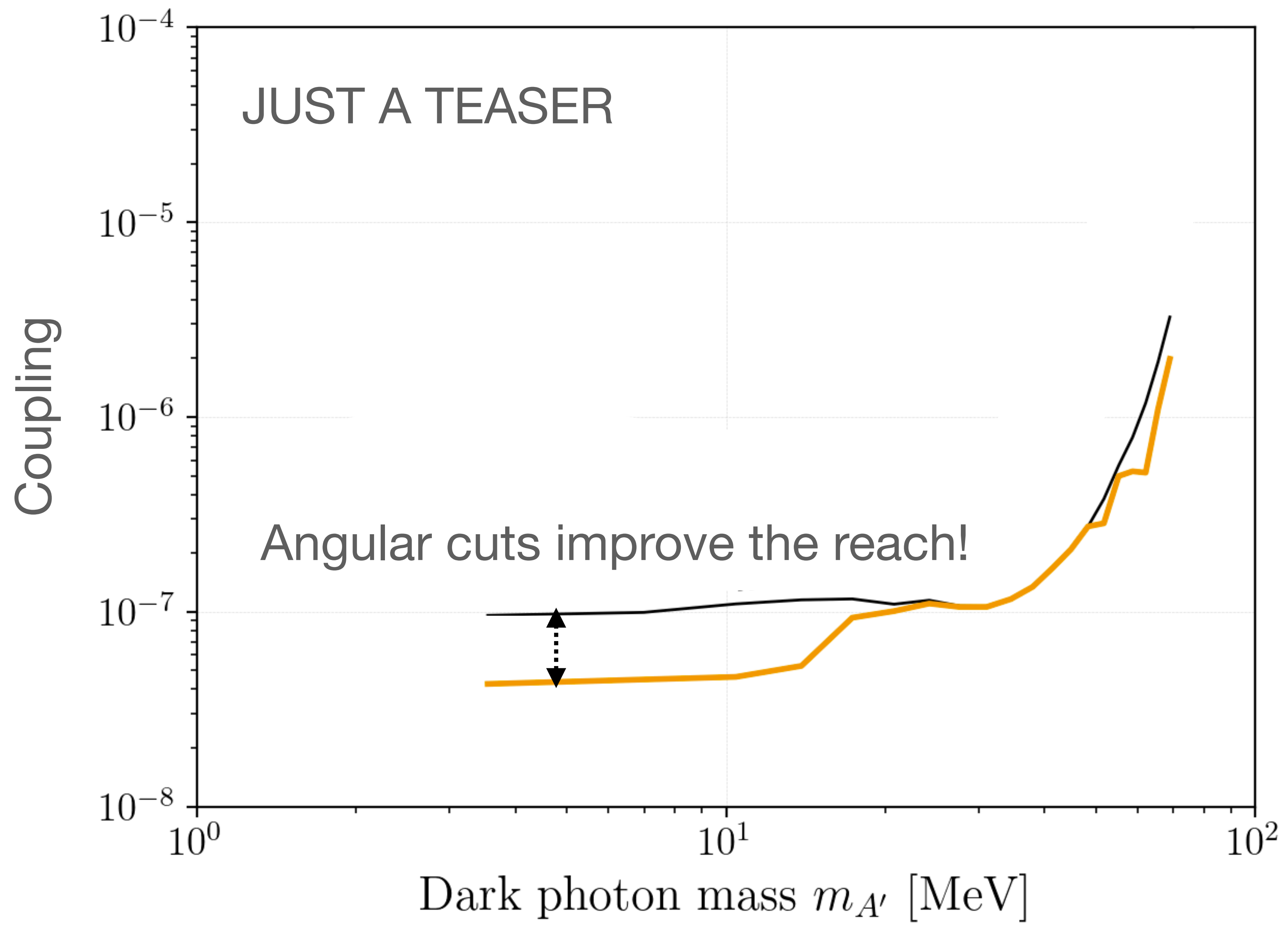
Conclusions

Light new physics opens new experimental opportunities for LFV experiments!

Testing the flavor properties of the axion at MEG II



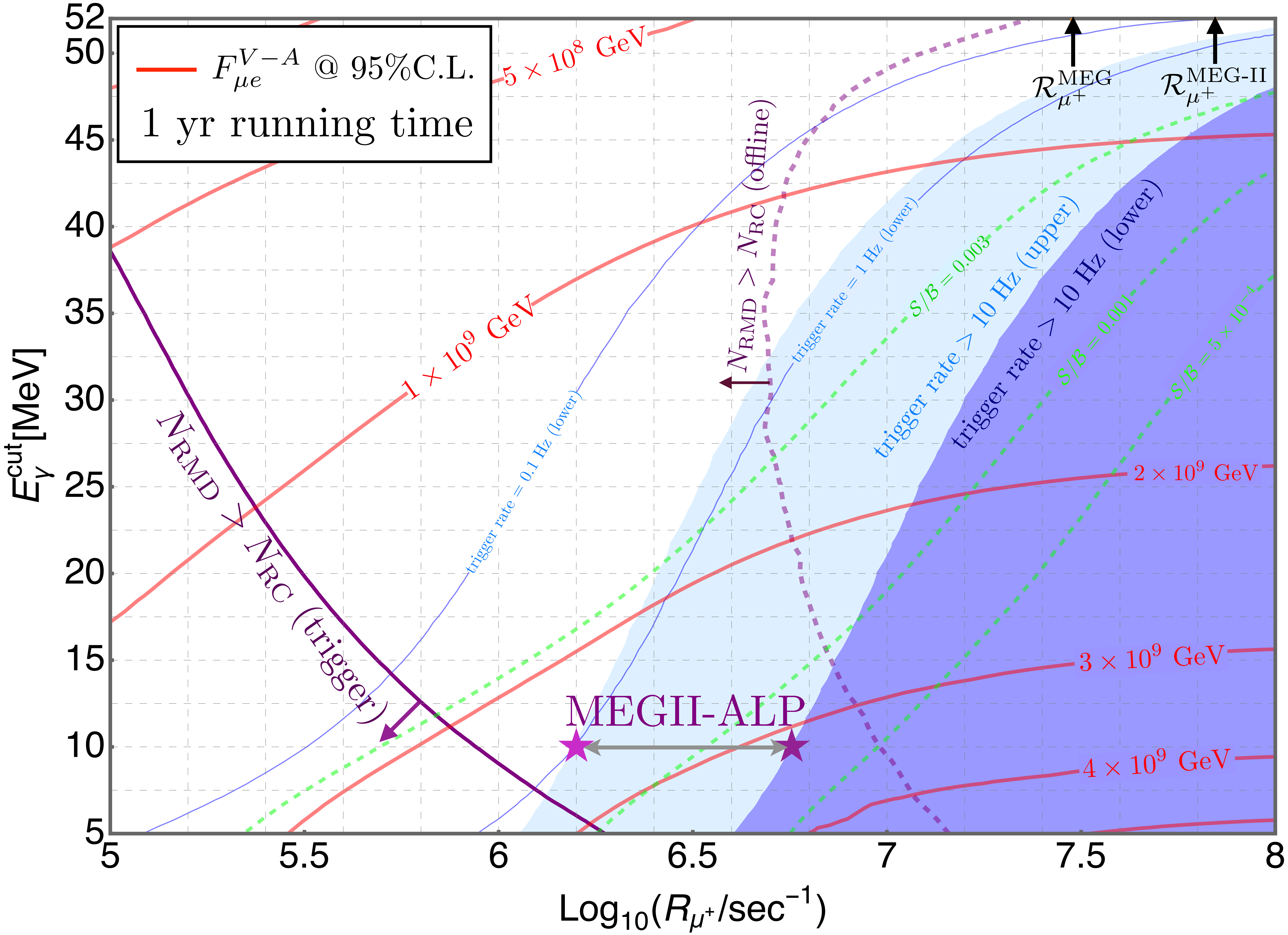
Testing the chirality of the dark photon at Mu3e



To be continued…


BACKUP

Final reach II



Systematics have to be controlled at per mill level (S/B is a good proxy)

How the trigger rate was estimated I

$$c_{\text{RMD}} \equiv \frac{N_{\text{RMD}}\big|_{\text{obs.}}}{N^{\text{MEG}}_{\mu^+,\text{tot}} \cdot \text{BR}^{\text{base}}_{\text{RMD}} \cdot \epsilon^{\text{trig.}}_{\text{RMD}} \cdot \epsilon^{\text{off.}}_{\text{RMD}} / \epsilon^{\text{trig.}}_{\text{RMD}}}$$

$$c_{\text{RMD}} \simeq 0.35$$

Known from MEG RMD paper

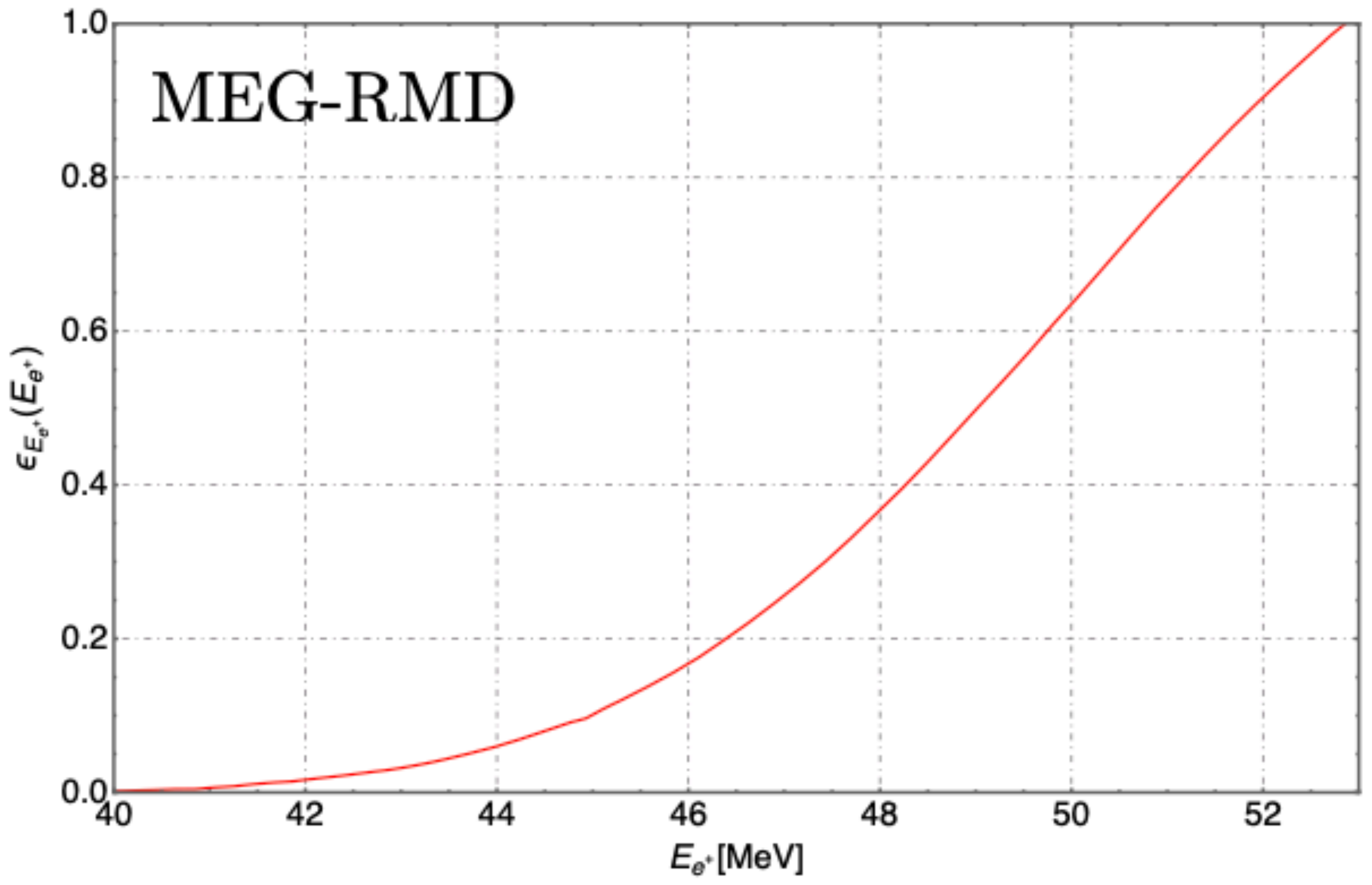
Known from MEG F

$E_e > 40$ MeV, $E_\gamma > 5$ MeV.

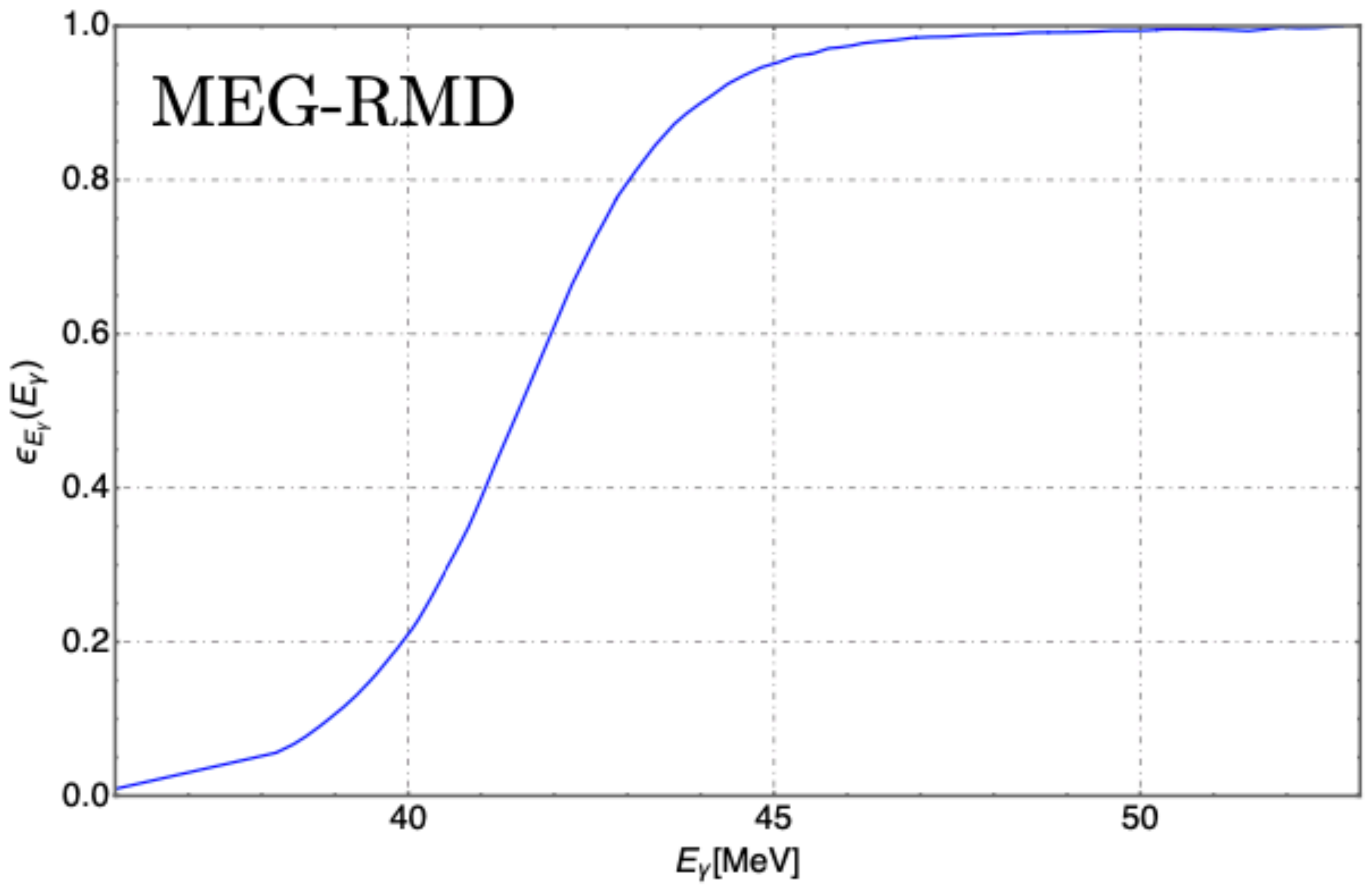
trigger efficiencies

trigger efficiencies+offline selection

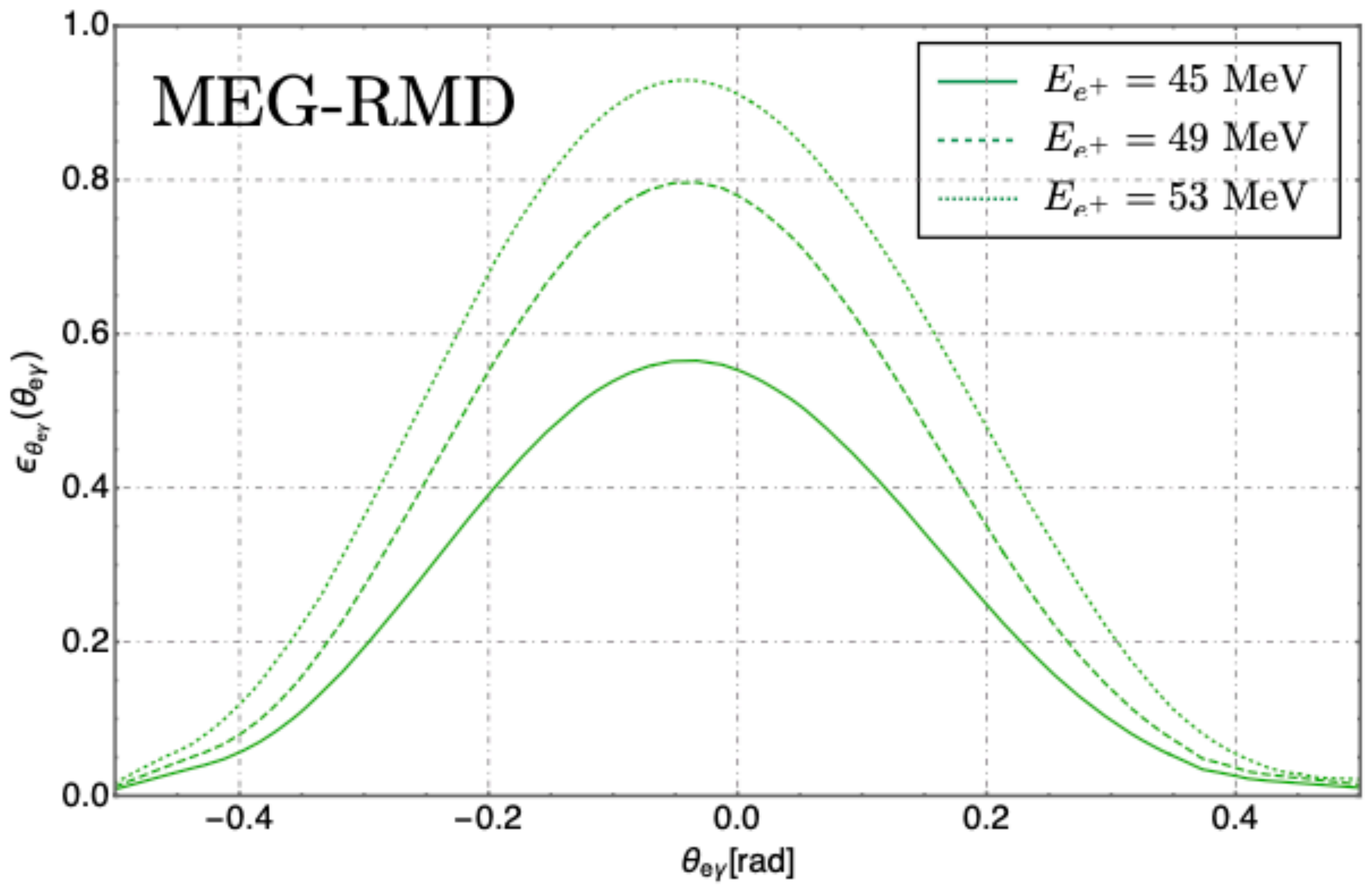
Positron energy >45 MeV @ hardware level



Photon >45 MeV @ trigger level



back to back topology @ trigger level



$$\epsilon^{\text{MEG}}_{\text{trigger}} \equiv \epsilon_{E_e}(E_e) \times \epsilon_{E_\gamma}(E_\gamma) \times \epsilon_{\theta_{e\gamma}}(E_e, \theta_{e\gamma})$$

How the trigger rate was estimated II

$$N^{\text{MEG}}_{\mu^+,\text{tot}} \cdot \text{BR}^{\text{base}}_{\text{RC}} \cdot \epsilon^{\text{trig.}}_{\text{RC}} \cdot \epsilon^{\text{off.}}_{\text{RC}}/\epsilon^{\text{trig.}}_{\text{RC}} = N_{\text{RC}}|_{\text{obs.}}$$

$$\text{BR}^{\text{base}}_{\text{RC}} = c_{\text{RC}} \cdot \text{BR}^{\text{base}'}_{\text{RMD}} \cdot \text{BR}^{\text{base}}_{\text{Mich.}} \cdot R_{\mu^+} \cdot \Delta t^{\text{trig.}}_{e\gamma}$$

ALL IN ALL

$$R^{\text{trig.}}_{\text{RMD}} \in \frac{N_{\text{RMD}}|_{\text{obs.}}}{\epsilon^{\text{off.}}_{\text{RMD}} \cdot t^{\text{MEG}}_{\text{run}}} \left(1, \frac{1}{c_{\text{RMD}}}\right) = (1.7 - 4.8) \cdot 10^{-2} \text{ Hz}$$

$$R^{\text{trig.}}_{\text{RC}} \in \frac{N_{\text{RC}}|_{\text{obs.}}}{\epsilon^{\text{off.}}_{\text{RC}} \cdot t^{\text{MEG}}_{\text{run}}} \left(1, \frac{1}{c_{\text{RC}}}\right) = (0.7 - 10) \text{ Hz}\,.$$

The c's factors give the size of our uncertainties in the trigger estimate